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Vegetation structure, aboveground biomass, and carbon storage of *wono*¸ a local forest management in Gunungkidul, Yogyakarta, Indonesia, across three geomorphological zones

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Abstract. *Tohirin, Suryanto P, Sadono R. 2021. Vegetation structure, aboveground biomass, and carbon storage of* wono¸ *local forest management in Gunungkidul, Yogyakarta, Indonesia, across three geomorphological zones. Biodiversitas 22: 3207-3218. Wono* is local community-based forest management in Gunungkidul District, Yogyakarta. This land use has the potential to reduce carbon dioxide emissions through their carbon sequestration capacity as well as to produce renewable energy sources through wood biomass for charcoal and wood pellet. Since Gunungkidul is unique in terms of geomorphological characteristics, study on the vegetation structure, biomass estimation, and carbon storage of *wono* across geomorphological zones are important. Therefore, this study describes the vegetation structure of *wono* in three geomorphological zones of Gunungkidul District, as well as estimates the aboveground living biomass (AGB) and aboveground living carbon storage (AGC). The quadratic sampling technique was used to collect data for vegetation analysis with the size of the plots were 20 m x 20 m, 10 m x 10 m, 5 m x 5 m, and 2 m x 2 m for trees, poles, saplings, and seedlings, respectively. A total of 32 plots were established, consisting of 18 plots in Nglanggeran Village, 12 plots in Dengok Village, and six plots in Girisekar Village, each village representing geomorphological zones of Batur Agung, Ledok Wonosari, and Pegunungan Sewu, respectively. The AGB was performed non-destructively and estimated using referenced allometric equations. Furthermore, the AGC was calculated using a conversion factor of 0.47 from the obtained AGB. The results showed that the identified species at *wono* in Batur Agung, Ledok Wonosari, and Pegunungan Sewu zones were 13, 7, and 8, respectively. *Swietenia macrophylla* had the highest important value index (IVI) of 185.22% in the Batur Agung zone, while *Tectona grandis* was the most important species in both the Ledok Wonosari and Pegunungan Sewu zones with IVI= 238.27% and 178.60%, respectively. The biodiversity in these three zones was very low in terms of species diversity (H' < 2) and species richness (R1 < 3.4). The estimated AGB and calculated AGC in the Batur Agung, Ledok Wonosari, and Pegunungan Sewu zones were 210.96 ton ha^{-1} and 99.15 ton C ha^{-1}, 73.58 ton ha^{-1} and 34.58 ton C ha^{-1}, and 57.92 ton ha^{-1} and 27.22 ton C ha^{-1}, respectively.

Keywords: Batur Agung, Dengok, Girisekar, Ledok Wonosari, Nglanggeran, species diversity and density, *wono*

Abbreviations: AGB: aboveground living biomass, AGC: aboveground living carbon storage, D: Simpson's index of diversity, DBH: diameter at breast height, E: Evenness index, H: total tree height, H': Shannon-Wiener diversity index, HKm: *Hutan Kemasyarakatan*, Ln: natural logarithm, n: total number of individuals of all species at the site, n_i: number of individuals of i^{th} species, N: total number of individuals of all species at the site, R1: Margalef's index, S: total number of species in the sample, ρ: tree density

INTRODUCTION

Plant biomass is increasingly important in the context of renewable energy potential and carbon storage. This resource is of great concern to ecologists and forest managers when considering climate change mitigation strategies (Khan et al. 2018). In the context of renewable energy, wood biomass can be used for charcoal bioenergy production (Kongprasert et al. 2019). The use of bioenergy from forest biomass shows a positive contribution to climate change mitigation (Withey et al. 2019). Biomass production can also be used as an indicator to assess forest productivity (Zhang et al. 2017).

Across the world, there is various land use management to produce wood biomass. In the United States, the prospect of increased use of woody biomass as a renewable energy source is dependent on supply from private forest land (Cai et al. 2016). In Southeast European countries (Croatia, Bosnia-Herzegovina, Serbia, and Macedonia), 38-55% of forest landowners are willing to manage their forests for wood biomass production (Stjepan et al. 2015). In the countries where social forestry is implemented in their policy (e.g., Indonesia), community-based forest management has the potential to produce wood biomass while at the same time can reduce carbon emissions in the atmosphere on a regional and global scale (Purwanto et al. 2012; Indrajaya and Sudomo 2016; Setiahadi 2017; Ivando et al. 2019; Wirabuana et al. 2020). Nonetheless, since there are various forms of community forestry in response to geographical and socio-cultural variation, biomass and carbon storage measurements must take into account a wide range of landscape conditions.

In Indonesia, the implementation of community forestry policy is proven to be successful in some areas. In Gunungkidul District, Yogyakarta, social forestry program promoted by the government, academics, communities and non-government organizations showed positive outcomes indicated by land cover improvement as the result of the massive rehabilitation activities on degraded lands in the district. In the 1970s - 2012 period, there was a trend of changing land cover from rocky and barren land to vegetated land covered with trees (Wardhana et al., 2012). For example, the Community Forestry Program (*Hutan Kemasyarakatan= HKm*) in Bleberan Village, Gunungkidul has changed the HKm area from degraded land to teak plantation forest by 82% in the period 2003 - 2018 (Sadono et al. 2020).

The landscape in Gunungkidul is very unique in terms of geological characteristics. Based on geomorphological conditions, Gunungkidul area is divided into three zones, namely Batur Agung, Ledok Wonosari, and Pegunungan Sewu which are located in the northern, middle, and southern parts, respectively. The Batur Agung zone in the north has lateritic volcanic soil and lithosol soil types with parent rock in the form of dacite and andesite. The Ledok Wonosari zone in the middle has soil types that develop in the form of grumusols from limestone and clay (alluvium) parent materials. The Pegunungan Sewu zone in the south is in the form of karst hills with a hilly topography composed of limestone. Furthermore, the character of land management in the three zones differs based on the land transitions that occur in each zone (Wardhana et al. 2012). Following Mather's transition model (1992), the Batur Agung has a higher dynamic than the two others. The Ledok Wonosari has a natural transition pattern. Interestingly, the Pegunungan Sewu has a drastic land transition dynamic after 1980.

The community of Gunungkidul recognizes three types of tree-based land use management, namely *pekarangan*, *tegalan*, and *wono*. *Pekarangan* is located surrounding the house and is usually planted with woody plants for construction, firewoods, crops, fruits, and food sources. *Tegalan* is separated from settlements by a certain distance and generally occupied by hardwood trees intercropped with short-cycle crops (Awang et al. 2002). *Wono* is characterized by its distance far from settlements and is dominated by forestry vegetation in the form of monoculture or polyculture (Awang et al. 2002). In comparison to *Pekarangan* and *Tegalan*, land cover in *wono* is unlikely to alter much in a short period. While benefiting the communities in fulfilling their daily needs, these land uses to play an important role in increasing biomass and enhancing carbon storage.

Research related to biomass and carbon storage of community forests in Gunungkidul District has been carried out by scholars (Askar et al. 2018; Indrajaya and Sudomo, 2016; Purwanto et al. 2012; Sulistyo et al. 2010). However, research on similar themes that focused specifically on *wono* is rarely found. Therefore, this study aims to investigate the vegetation structure, aboveground biomass, and carbon storage of *wono* across the three geomorphological zones in Gunungkidul area.

MATERIALS AND METHODS

Study area

The study was conducted in Gunungkidul District, Yogyakarta, Indonesia (Figure 1). This district covers an area of 1.485,36 km^2 and is located at 110°21' - 110°50' E and 7°46' - 8°09' S. The average daily temperature, minimum temperature, and maximum temperature are reported as 27.7°C, 23.2°C, and 32.4°C, respectively. The relative humidity ranges between 80% and 85%. Each year, the average number of wet months ranges from 5 to 7 months, while the number of dry months ranges from 4 to 6 months. The annual rainfall average is 2093.15 mm. According to the Schmidt-Ferguson classification, this area is in the climate type category C (slightly wet) and the tropical monsoon climate (Am) and based on the Koppen climate type.

In this study, three geomorphological zones were taken into account, namely Batur Agung, Ledok Wonosari, and Pegunungan Sewu with the altitudes of 200-700 m a.s.l, 150-200 m a.s.l, and 0-300 m a.s.l, respectively. A village was selected purposively for each zone, namely Nglanggeran, Dengok, and Girisekar representing Batur Agung, Ledok Wonosari, and Pegunungan Sewu, respectively (Fig. 1). The Batur Agung zone is shaped like a basin with the northern part forming a plateau that stretches from west to east and it curves slightly to the south in the west. The topography of the Batur Agung area is mostly mountainous with steep slopes with a slope of up to more than 45%. This zone is located in the north of Gunungkidul District, closer to the city of Yogyakarta, and has better infrastructure, making it easier to access education and health facilities outside the area. The Ledok Wonosari zone, located in the middle part of Gunungkidul District, has higher soil fertility than in the other two zones. This zone has a flat topography, except for some areas bordering the other physiographic units, which have wavy topography. The Pegunungan Sewu zone, located in the southern part of Gunungkidul District, is characterized by its constituent rocks in the form of limestone. The topography in this zone consists of small hills and steep slopes with narrow valleys and no water outflow between the hills. This zone is located quite far from the city center of Wonosari and is directly adjacent to the Indian Ocean.

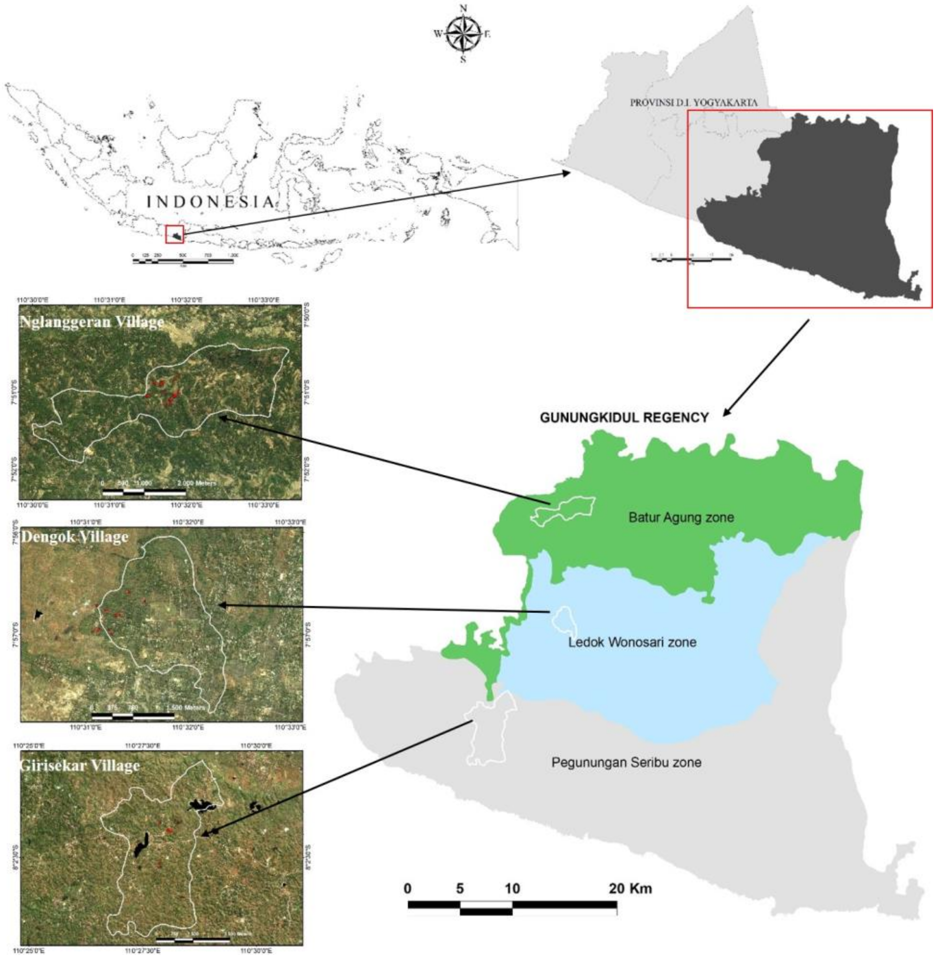


Figure 1. Study area of *wono* in Gunungkidul District, Yogyakarta, Indonesia. Three selected villages were Nglanggeran, Dengok, and Girisekar representing for three zones Batur Agung, Ledok Wonosari, and Pegunungan Sewu, respectively.

Data collection

The study was carried out between February and May 2021. This study used a stratified sampling technique that focused on land use in the form of *wono*. Field orientation and preliminary study were conducted before data collection to gain an understanding of the condition of *wono* in the three geomorphological zones. A quadratic sampling technique was used to collect vegetation data. The measuring plots used were 20 m x 20 m, 10 m x 10 m, 5 m x 5 m, and 2 x 2 m for trees, poles, saplings, and seedlings, respectively (Mueller-Dombois and Ellenbergh 1974). The total number of quadratic samples were 36 plots at selected farmer's *wono* in the determined three villages. Based on the homogeneity of the three zones, these 36 plots were allocated to the villages of Nglanggeran, Dengok, and Girisekar, with 18, 12, and 6 plots, respectively. Each plot in each village was distributed randomly at each farmer's *wono*. The number of plant species in the measurement plot was recorded for each life stage (trees, diameter ≥ 20 cm; poles, diameter= 10 - 19.9 cm; saplings, diameter < 10 cm, height > 150 cm; seedlings, height ≤ 150 cm). Furthermore, tree height, diameter at breast height (±1.30 m), and coordinate position were all measured (Suryanto et al. 2021).

Data analysis

Vegetation structure

The collected data were analyzed to describe the vegetation structure of *wono* in terms of density (stem ha^{-1}), relative density, relative frequency, relative dominance, and important value index. The following formula was used to calculate these parameters (Mueller-Dombois and Ellenbergh 1974):

$$Density = \frac{Number\ of\ individuals\ of\ the\ target\ species\ occured}{Total\ number\ of\ households}$$

$$Relative\ Density = \frac{Density\ of\ target\ species}{Density\ of\ all\ species} \times 100$$

$$Frequency = \frac{Number\ of\ households\ in\ which\ target\ species\ occured}{Total\ number\ of\ households}$$

$$Relative\ Frequency = \frac{Frequency\ of\ target\ species}{Frequency of\ all\ species} \times 100$$

$$Relative\ Dominance = \frac{Basal\ area\ of\ target\ species}{Basal\ area\ of\ all\ species} \times 100$$

$$Importance\ Value\ Index = Relative\ density + Relative\ frequency + Relative\ dominance$$

Furthermore, the Shannon-Wiener diversity index, the Simpson index of diversity, the Margalef index, and the Evenness index were all used in diversity analysis. These indices were calculated using the following formulas (Magurran 1988):

Shannon-Wiener diversity index (H')

$$H' = -\sum_{i=1}^{s}\left[\left(\frac{ni}{N}\right)Ln\left(\frac{ni}{N}\right)\right]$$

Where: H': Shannon-Wiener diversity index; ni: Number of individuals of i^{th} species; N: Total number of individuals of all species at the site; Ln: Natural logarithm

Simpson's index of diversity (D)
D = 1 - λ, with

$$\lambda = \sum_{i=1}^{s}\frac{ni\,(ni-1)}{n\,(n-1)}$$

Where: D: Simpson's index of diversity; ni: Number of individuals of i^{th} species; n: Total number of individuals of all species at the site

Margalef's index (R1)

$$R1 = \frac{S-1}{Ln\,(N)}$$

Where: R1: Margalef's index; S: Total number of species in the sample; Ln: Natural logarithm; N: Total number of individuals in the sample

Evenness index (E)

$$E = \frac{H'}{Ln\,(S)}$$

Where: E: Evenness index; H': Shannon-Wiener index; Ln: Natural logarithm; S: Total number of species in the sample

Aboveground living biomass and carbon storage

Tree biomass was measured using a non-destructive method that did not require tree cutting. The parameters used were the stem diameter at breast height (DBH) and total tree height (H) (Hairiah et al. 2010). Aboveground living biomass (AGB) was calculated in *wono* using all types of woody plants with DBH greater than or equal to 10 cm (Purwanto et al. 2012). The allometric equations used to calculate the estimated AGB for each species were depicted in Table 1.

Furthermore, the aboveground living carbon storage (AGC) was calculated by taking calculated ABG and multiplying it by a conversion factor of 0.47.(IPCC 2006). The estimation of AGC in *wono* was calculated using the formula:

AGC = AGB * 0.47

Where: AGC: aboveground living carbon storage (ton C ha^{-1}); AGB: aboveground living biomass (ton ha^{-1}); 0.47= conversion factor (IPCC 2006).

RESULTS AND DISCUSSION

Vegetation structure of *wono*

Batur Agung zone

A total of 948 individual plants belonged to 13 species were identified from 18 plots representing all life stages of standing vegetation in Batur Agung zone. The number of species in each life stage was three, seven, eight, and 10 species representing seedlings, saplings, poles, and trees, respectively. These identified species were *S. macrophylla*, *D. latifolia*, *P. falcataria*, *T. grandis*, *A. auriculiformis*, *Cocos nucifera* L., *Parkia speciosa* Hassk, *Gnetum gnemon* Linn., *Alstonia scholaris* R.Br., *Theobroma cacao* L., *Mangifera indica* L., *Archidendron pauciflorum* (Benth.) Nielsen, and *Hevea brasiliensis* (Willd. ex A. Juss.) Mull. Arg. The most dominant species in every life stage was always *S. macrophylla* with the following numbers: 346, 160, 77, and 133 individuals for seedlings, saplings, poles, and trees, respectively (Figure 2). The dominant *S. macrophylla* at *wono* in Nglanggeran Village of Batur Agung zone was consistent with community preferences; thus, this species was appropriate in this village and was frequently used as construction wood (Purwanto et al. 2012).

Plant density at seedlings, saplings, poles, and trees of life stages were 65278, 4067, 589, and 263 stems ha^{-1}, respectively (Table 2). The pattern of the horizontal structure was close to the reversed J-shape distribution or negative exponential distribution (Figure 3). Furthermore, the average basal area for poles and tree stages were 9.83 and 17.37 m^2 ha^{-1}, respectively. The average diameter was 14.31 and 28.03 cm for poles and tree stages, respectively. Meanwhile, the average height of the poles stage was 10.95 m, and the tree stage was 15.09 m.

Table 1. Allometric equations for estimating aboveground biomass for *Acacia auriculiformis*, *Tectona grandis*, *Swietenia macrophylla*, *Paraserianthes falcataria*, *Dalbergia latifolia*, unbranched trees, and other trees in *wono*

Species	Allometric equation	References
Acacia auriculiformis A. Cunn. ex Benth.	$AGB = 0.0775\ (DBH^2.H)^{0.9018}$	Purwanto et al. (2012)
Tectona grandis L.f.	$AGB = 0.0149\ (DBH^2.H)^{1.0835}$	Purwanto et al. (2012)
Swietenia macrophylla King	$AGB = 0.9029\ (DBH^2.H)^{0.6840}$	Purwanto et al. (2012)
Paraserianthes falcataria (L.) I.C. Nielsen	$AGB = 0.0199\ (DBH^2.H)^{0.9296}$	Purwanto et al. (2012)
Dalbergia latifolia Roxb	$AGB = 0.7458\ (DBH^2.H)^{0.6394}$	Purwanto et al. (2012)
Other trees	$AGB = 0.0240\ (DBH^2.H)^{0.7817}$	Purwanto et al. (2012)
Unbranched trees	$AGB = \pi\ \rho DBH^2H/40$	Hairiah et al. (1999)

Notes: AGB: aboveground living biomass (Kg $tree^{-1}$); DBH: stem diameter at breast height; H: total tree height; ρ: tree density, π= 3.14

Table 2. Vegetation Structure at *wono* in Nglanggeran Village of Batur Agung zone, Gunungkidul District, Indonesia

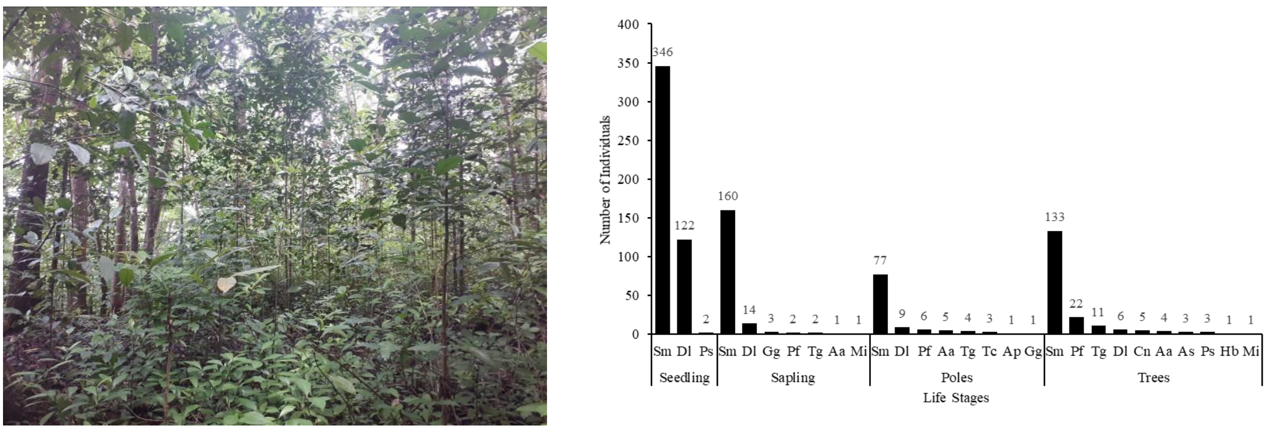
Life Stages	Species	Mean density (stems ha^{-1})	Stand basal area (m^2 ha^{-1})	Mean diameter (cm)	Mean tree height (m)
Seedling	Dl, Ps, Sm	65278 ± 11916	-	-	-
Sapling	Aa, Dl, Gg, Mi, Pf, Sm, Tg	4067 ± 585	-	-	-
Poles	Aa, Ap, Dl, Gg, Pf, Sm, Tc, Tg	589 ± 75	9.83 ± 1.154	14.31 ± 0.273	10.95 ± 0.249
Trees	Aa, As, Cn, Dl, Hb, Mi, Pf, Ps, Sm, Tg	263 ± 39	17.37 ± 2.956	28.03 ± 0.550	15.09 ± 0.184

Note: Data on mean density, stand basal areal, mean diameter, and mean tree height are presented in = mean ± standard error; Aa: *Acacia auriculiformis*; Ap: *A. pauciflorum*; As: *A. scholaris*; Cn: *C. nucifera*; Dl: *D. latifolia*; Gg: *G. gnemon*; Hb: *H. brasiliensis*; Mi: *M. indica*; Pf: *P. falcataria*; Ps: *P. speciosa*; Sm: *S. macrophylla*; Tc: *T. cacao*; and Tg: *T. grandis*

Table 3. Three most important species in term of IVI for each life stage and biodiversity indicators at *wono* in Nglanggeran Village in the Batur Agung zone, Gunungkidul District, Indonesia

Species	Relative density (%)	Relative frequency (%)	Relative dominance (%)	Importance value index (%)	Species richness	D	H'	R1	E
Seedlings									
Swietenia macrophylla	73.62	53.33	-	126.95	3	0.39	0.60	0.33	0.55
Dalbergia latifolia	25.96	43.33	-	69.29					
Parkia speciosa	0.43	3.33	-	3.76					
Saplings									
Swietenia macrophylla	87.43	54.84	-	142.27	7	0.23	0.54	1.15	0.28
Dalbergia latifolia	7.65	22.58	-	30.23					
Gnetum gnemon	1.64	6.45	-	8.09					
Poles									
Swietenia macrophylla	72.64	51.52	73.02	197.18	8	0.46	1.06	1.50	0.51
Dalbergia latifolia	8.49	18.18	8.98	35.65					
Paraserianthes falcataria	5.66	9.09	6.49	21.24					
Trees									
Swietenia macrophylla	70.37	42.86	71.99	185.22	10	0.49	1.14	1.72	0.49
Paraserianthes falcataria	11.64	11.90	14.61	38.16					
Tectona grandis	5.82	9.52	5.43	20.78					

Notes: D: Simpson's index, H': Shannon-Wiener index, R1: Margalef's index, E: Evenness index



A B

Figure 1. The condition of *wono* in Nglanggeran Village of Batur Agung zone, Gunungkidul District, Indonesia; A. Representation of the general picture, B. Number of individuals species in every life stage. Notes: Aa: *Acacia auriculiformis*; Ap: *A. pauciflorum*; As: *A. scholaris*; Cn: *C. nucifera*; Dl: *D. latifolia*; Gg: *G. gnemon*; Hb: *H. brasiliensis*; Mi: *M. indica*; Pf: *P. falcataria*; Ps: *P. speciosa*; Sm: *S. macrophylla*; Tc: *T. cacao*; and Tg: *T. grandis*

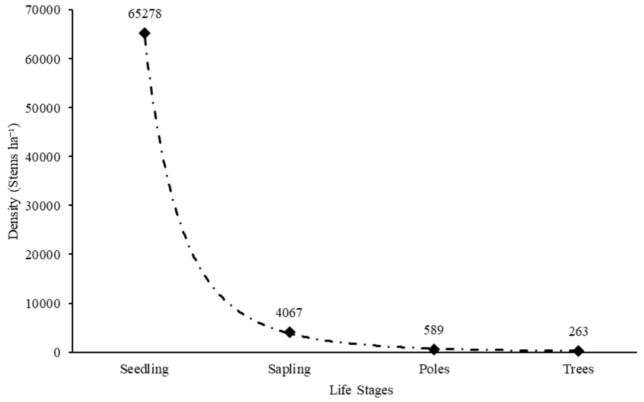


Figure 2. The density of each life stage of *wono's* vegetation in Nglanggeran Village of Batur Agung Zone, Gunungkidul District, Indonesia

The three highest IVI at the seedings stage were *S. macrophylla,* followed by *D. latifolia*, and *P. speciosa* with IVI= 126.95%, 69.29%, and 3.76%, respectively. *S. macrophylla* was also the highest IVI in the saplings stage with 142.27%, followed by *D. latifolia* with IVI= 30.23%, and *G. gnemon* with IVI= 8.09%. At the poles stage, *S. macrophylla was* still the highest, followed by *D. latifolia*, and *P. falcataria* with IVI= 197.18%, 35.65%, and 21.24%, respectively. *S. macrophylla* was also the highest IVI at the trees stage with 185.22%, followed by *P. falcataria* with IVI= 38.16%, and *T. grandis* with IVI= 20.78% (Table 3). Furthermore, the species richness of all life stages was classified into the low category with R1< 3.4. The highest species diversity was found in the trees stage with H' value= 1.14, followed by poles, seedlings, and saplings with H' values= 1.06, 0.60, and 0.54, respectively. These species diversity figures were included in the low category since the obtained H' values were lower than 2 (Magurran 1988). Meanwhile, for the evenness of species, the three life stages of seedlings, poles, and trees were in the medium category with E value between 0.3 and 0.6. However, the evenness of the saplings stage was in a low category with E value lower than 0.3.

Ledok Wonosari zone

A total of 234 individual plants belonged to seven species were identified from 12 plots, representing all life stages of standing vegetation in Ledok Wonosari zone. The number of species in each life stage was three, four, four, and five species representing seedlings, saplings, poles, and trees, respectively. These identified species were *S. macrophylla, T. grandis, D. latifolia, A. auriculiformis, Anacardium occidentale* L., *Ceiba pentandra* (L.) Gaertn., and *Samanea saman* (Jacq.) Merr. *T. grandis* was the most dominant species at saplings, poles, and tree stages with 37, 62, and 60 individuals, respectively, while *S. macrophylla* was the most dominant at the seedlings stage with 34 individuals (Figure 4).

Plant density at seedlings, saplings, poles, and trees of all four life stages were 11042, 1467, 567, and 144 stems ha^{-1}, respectively (Table 4). The pattern of the horizontal structure was close to the reversed J-shape distribution or negative exponential distribution (Figure 5). Furthermore, the average basal area for poles and tree stages were 9.26 and 7.80 m^2 ha^{-1}, respectively. The average diameters were 14.18 and 25.25 cm for poles and tree stages, respectively. Meanwhile, the average height of the poles stage was 10.24 m, and the tree stage was 11.67 m.

In terms of IVI, *S. macrophylla* was the highest at seedling stage with IVI= 107.90%, followed by *T. grandis* with IVI= 76.42%, and *D. latifolia* with IVI= 15.68%. However, *T. grandis* was the highest IVI in the next three life stages (Table 5). At the saplings stage, the IVI of *T. grandis* was the highest with 148.38%, followed by *S. macrophylla* with 30.52%, and *D. latifolia* with 11.69%. At the poles stage, *T. grandis was* the highest with IVI= 254.43%, followed by *A. auriculiformis* with IVI= 19.81%, and *S. macrophylla* with IVI= 15.61%. At the highest life stage, the IVI of *T. grandis* was the highest with 238.27%, followed by *S. saman* with 28.44%, and *S. macrophylla* with 16.49%. Furthermore, the species richness of all life stages was categorized into the low category with R1< 3.4. The highest species diversity was found in the life stage of seedlings with H' value= 0.86, followed by saplings, trees, and poles with H' values: 0.59, 0.54, and 0.39, respectively. The level of plant species diversity at all life stages was included in the low category, where the obtained H' values were lower than 2 (H' < 2). For the evenness species of all life stages, seedlings were in the high category with E value higher than 0.6, saplings and trees were in the medium category with E values between 0.3 to 0.6, and the poles were in the medium category with E value lower than 0.3.

Table 4. Vegetation Structure at *wono* in Dengok Village of Ledok Wonosari zone, Gunungkidul District, Indonesia

Life stages	Species	Mean density (stems ha^{-1})	Stand basal area (m^2 ha^{-1})	Mean diameter (cm)	Mean tree height (m)
Seedling	Dl, Sm, Tg	11042 ± 3502	-	-	-
Sapling	Ao, Dl, Sm, Tg	1467 ± 377	-	-	-
Poles	Aa, Sm, Ss, Tg	567 ± 104	9.26 ± 2.085	14.18 ± 0.328	10.24 ± 0.155
Trees	Aa, Cp, Sm, Ss, Tg	144 ± 16	7.80 ± 1.721	25.25 ± 0.881	11.67 ± 0.132

Note: Data on mean density, stand basal areal, mean diameter, and mean tree height are presented in = mean ± standard error; Aa: *A. auriculiformis*; Dl: *D. latifolia*; Sm: *S. macrophylla*; Tg: *T. grandis*; Ao: *A. occidentale*; Cp: *C. pentandra*; and Ss: *S. saman*

Table 5. Three most important species in terms of IVI for each life stage and biodiversity indicators at *wono* in Dengok Village of Ledok Wonosari zone, Gunungkidul District, Indonesia

Species	Relative density (%)	Relative frequency (%)	Relative dominance (%)	Importance value index (%)	Species richness	D	H'	R1	E
Seedling									
Swietenia macrophylla	64.15	43.75	-	107.90	3	0.52	0.86	0.50	0.78
Tectona grandis	26.42	50.00	-	76.42					
Dalbergia latifolia	9.43	6.25	-	15.68					
Sapling									
Tectona grandis	84.09	64.29	-	148.38	4	0.29	0.59	0.79	0.43
Swietenia macrophylla	9.09	21.43	-	30.52					
Dalbergia latifolia	4.55	7.14	-	11.69					
Poles									
Tectona grandis	91.18	73.33	89.92	254.43	4	0.17	0.39	0.71	0.28
Acacia auriculiformis	2.94	13.33	3.54	19.81					
Swietenia macrophylla	4.41	6.67	4.53	15.61					
Trees									
Tectona grandis	86.96	64.71	86.61	238.27	5	0.24	0.54	0.94	0.33
Samanea saman	7.25	11.76	9.43	28.44					
Swietenia macrophylla	2.90	11.76	1.83	16.49					

Note: D: Simpson index; H': Shannon-Wiener index; R1: Margalef's index; E: Evenness index

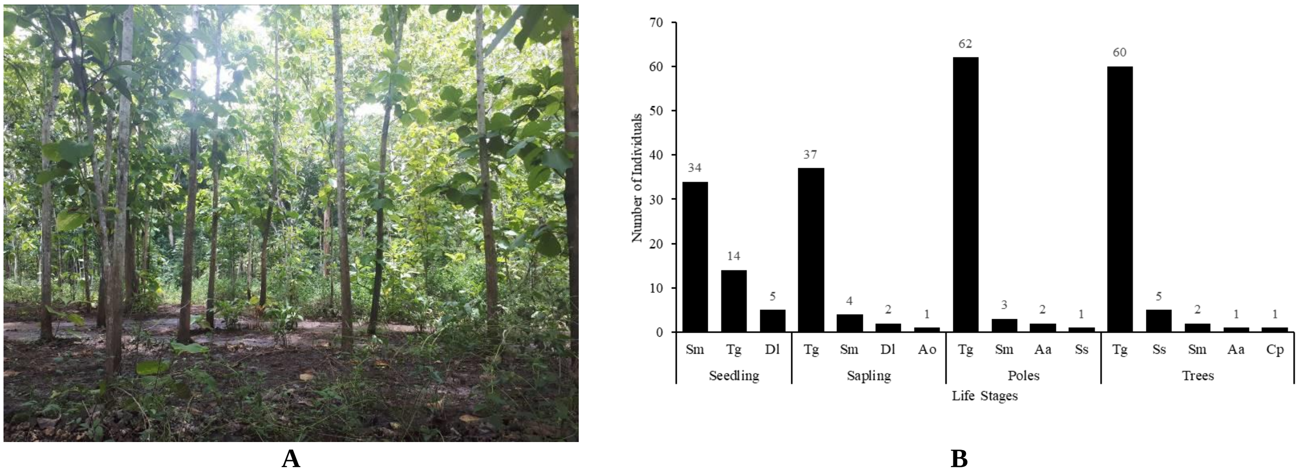


Figure 3. The condition of *wono* in Dengok Village of Ledok Wonosari zone, Gunungkidul District, Indonesia; A. Representation of the general picture, B. Number of individuals per species in each life stage. Notes: Aa: *A. auriculiformis*; Dl: *D. latifolia*; Sm: *S. macrophylla*; Tg: *T. grandis*; Ao: *A. occidentale*; Cp: *C. pentandra*; and Ss: *S. saman*

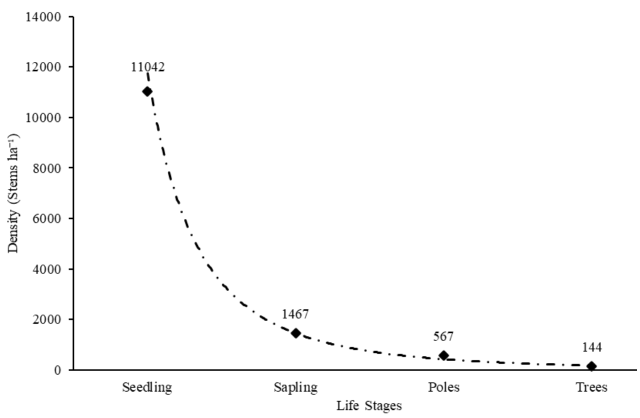


Figure 4. The density of each life stage on *wono's* vegetation in Dengok Village of Ledok Wonosari zone, Gunungkidul District, Indonesia

Pegunungan Sewu zone

A total of 234 individual plants belonged to eight species were identified from six plots, representing all life stages of standing vegetation in Pegunungan Sewu zone. The number of species in each life stage was three, five, four, and three species representing seedlings, saplings, poles, and trees, respectively. These identified species were *S. macrophylla*, *T. grandis*, *A. auriculiformis*, *D. latifolia*, *P. falcataria*, *Annona muricata* L., *Santalum album L.*, and *Senna siamea* (Lam.) Irwin & Barneby. *S. macrophylla* was the most common species found in seedlings, *A. auriculiformis* was found in saplings, and *T. grandis* was found in both poles and trees (Figure 6).

Plant density at seedlings, saplings, poles, and trees of all four life stages were 24584, 2934, 359, and 117 stems ha^{-1}, respectively (Table 6). The pattern of the horizontal structure was close to the reversed J-shape distribution or negative exponential distribution (Figure 7). Moreover, the average basal area for poles and trees were 6.15 and 5.14 m^2 ha^{-1}., respectively. The average diameter was 14.54 and 23.46 cm for poles and tree stages, respectively. Meanwhile, the average height of the poles stage was 9.22 m, and the trees stage was 11.25 m.

For the three highest IVI, *S. macrophylla* was the highest at seedlings stage with IVI= 136.44%, followed by *T. grandis* with IVI= 41.81%, and *D. latifolia* with IVI= 21.75%. However, *T. grandis* was the highest IVI in the next three life stages (Table 7). At the saplings stage, *T. grandis* was the highest with IVI= 71.82%, followed by *A. auriculiformis* with IVI= 68.64%, and *S. album* with IVI= 25.91%. At the poles stage, *T. grandis* was the highest with IVI= 184.36%, followed by *S. macrophylla* with IVI= 50.10%, and *A. auriculiformis* with IVI= 47.57%. At the trees stage, the IVI of *T. grandis* was the highest with 178.60%, followed by *S. macrophylla* with 98.08%, and *P. falcataria* with 23.31%. Furthermore, the level of species richness of all life stages was classified into the low category with R1< 3.4. The highest species diversity was found at the life stage of saplings with H' value= 1.36, followed by poles with H' value= 0.92, trees with H' value= 0.77, and seedlings with H' value= 0.49. The level of species diversity at all life stages of *wono* was classified into the low category with H' value< 2. For the evenness of species, the life stage of seedlings was in the medium category with E value between 0.3 and 0.6, and the life stage of saplings, poles, and trees was in the high category with E value > 0.6. These biodiversity indices showed a different figure in each life stage, and also in each investigated three zones, then species diversity was mainly influenced by rainfall, temperature, altitude, and latitude (Cowles et al. 2018; Xu et al. 2017).

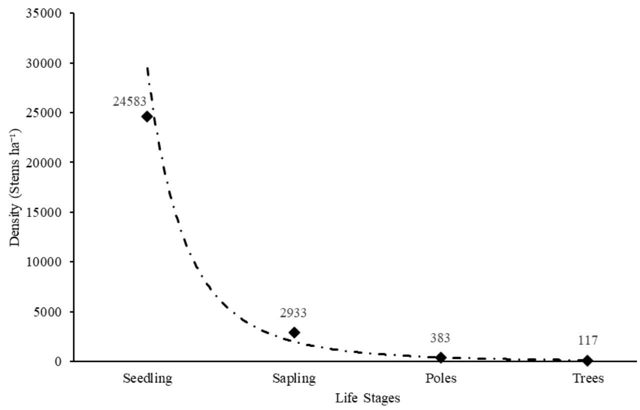
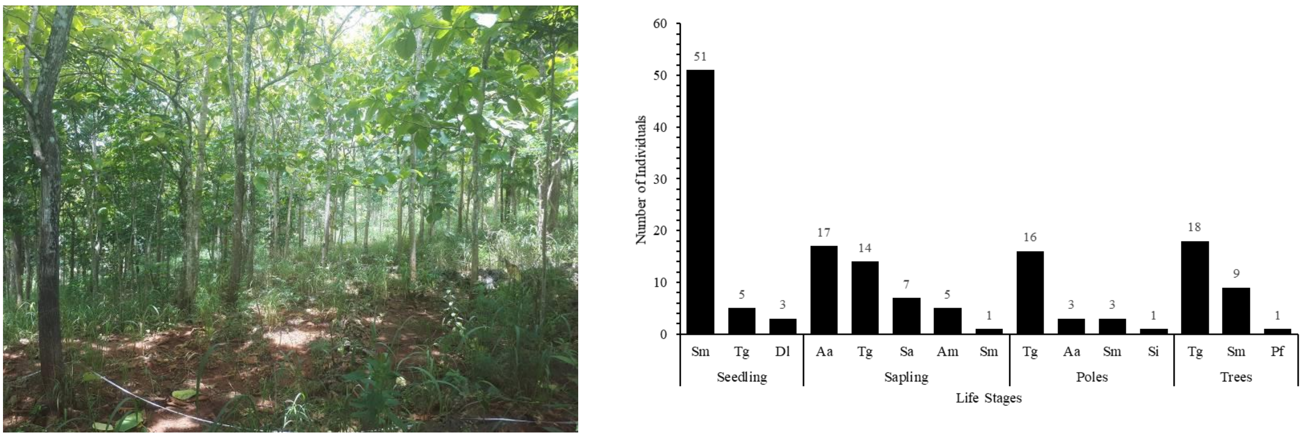


Figure 5. The density of each life stage of *wono's* vegetation in Girisekar Village of Pegunungan Sewu zone, Gunungkidul District, Indonesia



A **B**

Figure 6. The condition of *wono* in Girisekar Village of Pegunungan Sewu zone, Gunungkidul District, Indonesia; A. Representation of the general picture, B. Number of individuals per species in every life stage. Notes: Aa: *A. auriculiformis*; Dl: *D. latifolia*; Pf: *P. falcataria*; Sm: *S. macrophylla*; Tg: *T. grandis*; Am: *A. muricata* L.; Sa: *S. album*; and Si: *S. siamea*

Table 6. Vegetation structure at *wono* in Girisekar Village of Pegunungan Sewu zone

Life Stages	Species	Mean density (stems ha^{-1})	Stand basal area (m^2 ha^{-1})	Mean diameter (cm)	Mean tree height (m)
Seedling	Dl, Sm, Tg	24584 ± 13562	-	-	-
Sapling	Aa, Am, Sa, Sm, Tg	2934 ± 995	-	-	-
Poles	Aa, Si, Sm, Tg	359 ± 142	6.15 ± 2.910	14.54 ± 0.642	9.22 ± 0.321
Trees	Pf, Sm, Tg	117 ± 53	5.14 ± 2.306	23.46 ± 0.610	11.25 ± 0.176

Note: Data on mean density, stand basal areal, mean diameter, and mean tree height are presented in = mean ± standard error*;* Aa: *A. auriculiformis*; Dl: *D. latifolia*; Pf: *P. falcataria*; Sm: *S. macrophylla*; Tg: *T. grandis*; Am: *A. muricata* L.; Sa: *S. album*; and Si: *S. siamea*

Table 7. Three most important species in terms of IVI for each life stage and biodiversity indicators at *wono* in Girisekar Village of Pegunungan Sewu zone

Species	Relative density (%)	Relative frequency (%)	Relative dominance (%)	Importance value index (%)	Species richness	D	H'	R1	E
Seedlings									
Swietenia macrophylla	86.44	50.00	-	136.44	3	0.25	0.49	0.49	0.44
Tectona grandis	8.47	33.33	-	41.81					
Dalbergia latifolia	5.08	16.67	-	21.75					
Saplings									
Tectona grandis	31.82	40.00	-	71.82	5	0.73	1.36	1.06	0.84
Acacia auriculiformis	38.64	30.00	-	68.64					
Santalum album	15.91	10.00	-	25.91					
Poles									
Tectona grandis	69.57	44.44	70.35	184.36	4	0.50	0.92	0.96	0.66
Swietenia macrophylla	13.04	22.22	14.83	50.10					
Acacia auriculiformis	13.04	22.22	12.30	47.57					
Trees									
Tectona grandis	64.29	50.00	64.32	178.60	3	0.50	0.77	0.60	0.70
Swietenia macrophylla	32.14	33.33	32.61	98.08					
Paraserianthes falcataria	3.57	16.67	3.08	23.31					

Note: D: Simpson index, H': Shannon-Wiener index, R1: Margalef's index, E: Evenness index

Aboveground biomass and carbon storage

At *wono* in Nglanggeran Village of Batur Agung zone, 13 woody plant species were identified, including *S. macrophylla*, *P. falcataria*, *D. latifolia*, *T. grandis*, *A. auriculiformis*, and six other species identified as "other trees" and *C. nucifera* for the unbranched tree. The six identified species classified to other trees were *A. scholaris*, *P. speciosa*, *A. pauciflorum*, *G. gnemon*, *M. indica*, *H. brasiliensis*, and *T. cacao*.

The plant density of *S. macrophylla* was the highest, followed by *P. falcataria*, *D. latifolia*, other trees, *T. grandis*, and *A. auriculiformis* with 613 stems ha^{-1}, 64 stems ha^{-1}, 58 stems ha^{-1}, 46 stems ha^{-1}, 38 stems ha^{-1}, and 33 stems ha^{-1}, respectively (Table 8). Because it had the highest wood stem density, *S. macrophylla* was the most important species, accounting for 71.94 percent of the total (Weigel et al. 2018; Wirabuana et al. 2021). This species was also identified as one of the major contributors to aboveground biomass and carbon storage in community forests in Sambak Village, Magelang District, Central Java Province (Zulkarnaen 2020). Furthermore, the findings of this study supported previous findings that *S. macrophylla* was the most dominant species with 41.70% as a vegetation constituent of community forests in Nglanggeran Village (Purwanto et al. 2012).

An estimated AGB of 210.96 tons ha^{-1} was obtained from *wono* in Batur Agung zone. *S. macrophylla, P. falcataria, D. latifolia, T. grandis, A. auriculiformis*, other trees, and unbranched tree contributed AGB estimates of 182.38, 8.62, 7.60, 7.21, 3.70, 0.45, and 1.00 tons ha^{-1}, respectively. The obtained AGB of 210.96 tons ha^{-1} was equivalent to 99.15 tons C ha^{-1} of AGC. This carbon storage potential consisted of *S. macrophylla, P. falcataria, D. latifolia, T. grandis, A. auriculiformis,* other trees, and unbranched tree with calculated AGC of 85.72, 4.05, 3.57, 3.39, 1.74, 0.21, and 0.47 tons C ha^{-1}, respectively. The calculated AGC of this study was higher than that of Purwanto et al. (2012), who found that the total AGC of the community forest in Nglanggeran Village was 19.053 tons C ha^{-1}. Then, this study focused only on *wono*, where stem density was higher than in *Pekarangan* and *Tegal* (Purwanto et al. 2012). As a result, the *wono* has higher AGB and AGC than the *Pekarangan* and *Tegal*. This was consistent with the findings of Wirabuana et al. (2021), who discovered that the density of stands influences the production of biomass and carbon storage. On the other hand, Purwanto et al. (2012) investigated the community forest, which included not only *wono* but also *Pekarangan* and *Tegal*.

Five woody plant species were identified at *wono* in Dengok Village of the Ledok Wonosari zone, consisting of *T. grandis*, *S. macrophylla*, *A. auriculiformis*, and other two trees species, namely: *C. pentandra* and *S. saman*. Surprisingly, *T. grandis* was the dominant species in this zone, occupying more than 90% of the available area with a stand density of 642 stems ha^{-1}. This species domination was consistent with the findings of Aminudin (2008), who reported that *T. grandis* was the most dominant species, occupying 65.17% of the community forest in Dengok Village. In addition, both *S. macrophylla* and *A. auriculiformis* species had a density of around 48 stems ha^{-1}, while the other tree species had a density of 21 stems ha^{-1}.

Table 8. Tree species, density, mean diameter, mean tree height, estimated aboveground living biomass (AGB), and aboveground living carbon (AGC) of *wono* in the Batur Agung, Ledok Wonosari, and Pegunungan Sewu zone of Gunungkidul District, Indonesia

Species	**Density (stems ha^{-1})**	**Relative density (%)**	**Mean diameter (cm)**	**Mean tree height (m)**	**AGB (ton ha^{-1})**	**AGC (ton C ha^{-1})**
Batur Agung zone						
Swietenia macrophylla	613	71.94	23.22 ± 0.638	13.29 ± 0.160	182.38	85.72
Paraserianthes falcataria	64	7.50	28.11 ± 1.860	18.18 ± 0.732	8.62	4.05
Dalbergia latifolia	58	6.85	18.03 ± 1.169	11.80 ± 0.812	7.60	3.57
Tectona grandis	38	4.40	24.49 ± 1.857	14.87 ± 1.073	7.21	3.89
Acacia auriculiformis	33	3.92	18.33 ± 2.607	12.23 ± 0.955	3.70	3.39
Other trees	39	4.57	19.10 ± 2.261	11.24 ± 1.360	0.45	0.21
Unbranched trees	7	0.82	20.06 ± 0.000	11.40 ± 0.246	1.00	0.47
Total	**851**	**100.00**			**210.96**	**99.15**
Ledok Wonosari zone						
Tectona grandis	642	90.32	19.55 ± 0.706	11.00 ± 0.126	65.27	30.68
Swietenia macrophylla	29	4.11	16.94 ± 1.969	10.80 ± 0.735	5.69	2.68
Acacia auriculiformis	19	2.64	18.63 ± 3.196	11.67 ± 0.334	2.17	1.02
Other trees	21	2.93	25.74 ± 3.623	10.15 ± 0.509	0.45	0.21
Total	**710**	**100.00**			**73.58**	**34.58**
Pegunungan Sewu zone						
Tectona grandis	342	68.33	19.29 ± 0.950	9.98 ± 0.252	29.91	14.06
Swietenia macrophylla	88	17.50	21.65 ± 1.357	11.50 ± 0.469	23.83	11.20
Acacia auriculiformis	50	10.00	14.17 ± 1.899	10.34 ± 0.334	3.85	1.81
Paraserianthes falcataria	4	0.83	21.96 ± 0.000	11.00 ± 0.000	0.24	0.11
Other trees	17	3.33	11.31 ± 0.000	8.00 ± 0.000	0.09	0.04
Total	**500**	**100.00**			**57.92**	**27.22**

Note: Data on mean diameter and mean tree height are presented in = mean ± standard error

The estimated AGB of *wono* in the Ledok Wonosari zone was 73.58 ton ha^{-1}, consisting of 65.27, 5.69, 2.17, and 0.45 ton ha^{-1} from the following species: *T. grandis, S. macrophylla, A. auriculiformis*, and other species, respectively. This AGB estimate was equivalent to 34.58 ton C ha^{-1} of AGC. These AGB and AGC values were lower than those obtained by Aminudin (2008), who found that the biomass and carbon storage potential from community forests in Dengok Village were 135.95 ton ha^{-1} and was 66.33 ton C ha^{-1}. Then, the finding of this study calculated the ABG and AGC only in woody plants with a diameter greater than 10 cm, ignoring other AGB and AGC sources. In comparison to the Batur Agung zone above, this zone's figure was about a third because of differences in the number of identified species and species density, resulting in variations in biomass production as well as carbon storage potential (Weigel et al. 2018; Wirabuana et al. 2021). Moreover, the dimensions of the constituent species in the Batur Agung zone were in general larger in stem diameter and higher in total tree height.

The same number of identified species were also found at *wono* in Girisekar Village of Pegunungan Sewu zone, including *T. grandis, S. macrophylla, A. auriculiformis, P. falcataria*, and one other species for other trees, namely *S. siamea*. *T. Grandis* was also dominated in this zone, occupying up 68.3% of the available area. This finding was consistent with the occupation rate of this species in the same village as well as in Jetis Village, Gunungkidul District (Askar et al. 2018). According to the previous finding, *T. grandis* had up to 63,82% dominance in both villages. Furthermore, in ascending order, the density of constituting species in this zone was as follows: *T. grandis, S. macrophylla, A. auriculiformis, S. siamea*, and *P. falcataria*, and with 342, 88, 50, 17, and 4 stems ha-1, respectively.

The obtained AGB in *wono* in Pegunungan Sewu zone was estimated to be 57.92 ton ha^{-1}. This total estimate consisted of 29.91, 23.83, 3.85, 0.24, and 0.09 tons ha^{-1} representing the contribution of *T. grandis, S. macrophylla, A. auriculiformis, P. falcataria,* and *S. siamea*, respectively. This obtained AGB was equivalent to 27.22 ton C ha^{-1}. The finding of obtained AGB in this study was lower than that of Askar et al. (2018), who found that the total AGB of 72.54 ton ha^{-1} in Girisekar Village and Jetis Village. The applied method of the investigation was responsible for this difference in obtained AGB. This study relied on terrestrial observation, whereas the previous study relied on aerial Sentinel-2 imagery interpretation. Furthermore, the difference of conversion factor resulted in a difference in AGC value. The previously obtained AGC of 36.72 ton C ha^{-1} was calculated using a conversion factor of 0.5, which was 0.03 higher than the AGC obtained in this study with a conversion factor of 0.47. In addition, this zone's figure was lower in comparison to the Ledok Wonosari zone above due to differences in species density, which resulted in variations in biomass production as well as carbon storage potential (Weigel et al. 2018; Wirabuana et al. 2021).

The AGB estimates in the three zones focused in this study provided useful information to support the possibility of producing charcoal or wood pellet as a renewable energy source. In 2015, total charcoal production from community forests in Gunungkidul District was reported to be 81.46 tons (DPMPT Kabupaten Gunungkidul 2016). Despite the fact that 51.39% of households in the district have already used LPG as a cooking fuel, 0.21% of households continued to use charcoal as their primary fuel for cooking (BPS DIY 2020). The possibility of using woody plant species, such as *Tamarindus indica* L. and *S. macrophylla* from community forests to produce charcoal was also discovered in Bangunjiwo Village, Bantul District, with a total yield of 12.067 ton ha^{-1}, equivalent to Rp. 21,117,250.00 ha^{-1} (Purwanto and Ginting 2011). However, increasing the use of wood biomass from community forests for renewable energy sources will raise the price of timber as well as timber harvesting (Lauri et al. 2012), and may have global warming implications (de Bikua et al. 2020). Land cover changes from forested to open land can reduce carbon stores. For example, in Bleberan Village of Gunungkidul District, illegal logging on 40 Ha investigated areas resulted in 1040.53 decreases in carbon storage from 1999 to 2003 (Sadono et al. 2020).

The information provided by the AGC at *wono* in Gunungkidul District may be useful in supporting the program to reduce greenhouse gas (GHG) emissions in the forestry sector. This sector is the largest contributor to the GHG emission reduction target of 17.2% in the Nationally Determined Contribution, compared to other targets of total emissions of 29% under Business As Usual scheme in 2030 (Direktorat Jenderal Pengendalian Perubahan Iklim 2017). Consequently, preserving forested land to reduce emissions might have an effect on the rate of economic growth (Nurfatriani et al. 2019). Therefore, as compensation for the loss of forest economic value, the environmental services provided by forests must be commercially valued and integrated into market mechanisms (Farley 2012). Then, environmental services were thought to have the potential to realize the concept of sustainable development while also lowering poverty levels (Silori 2015).

Forest area management could be directed toward three goals, namely carbon sinks, carbon storage, and carbon emission reduction (Nurfatriani et al. 2019). The results of this study suggest that *wono* has to be included in the strategies of carbon emissions reduction along with the compensation mechanism. *wono* is more than just a forest area; it also has a high potential for social, economic, or environmental value and is linked to broader development interests. If this *wono* could be preserved as a forest, it would benefit a wide range of interests. Compensation payments for these benefits could be made through a variety of transaction schemes, including Purchasing Development Right (PDR), Payment for Environmental Service, and Liability Rule (Nurfatriani et al. 2015). Among these three schemes, PDR had the potential to assist *wono* with carbon emission reduction efforts (Nurfatriani et al. 2019). Furthermore, forest management for climate change mitigation is best applied in forest areas through community and government collaboration in the form of HKm for land rehabilitation (Rakatama et al. 2018). Based on formal regulation, this HKm could be implemented in a variety of forest functions, including production, conservation, and protected forest.

In conclusion total of 13 plant species were identified in *wono* from 18 sampling plots in Nglanggeran Village, Batur Agung zone with four dominant species were *S. macrophylla*, *D. latifolia*, *P. falcataria*, and *T. grandis*. There were seven species identified from 12 sampling plots in Dengok Village, Ledok Wonosari zone with three dominant species were *T. grandis*, *S. macrophylla*, and *D. latifolia*. Eight species were identified from six sampling plots in Girisekar Village in the Pegunungan Sewu zone with three dominant species were *T. grandis*, *S. macrophylla*, and *A. auriculiformis*. Furthermore, the biodiversity of *wono* in Nglanggeran Village has a higher species diversity index than in Girisekar Village and Dengok Village. The values of the Shannon-Wiener index for the pole and the tree were 1.06 and 1.14, 0.92 and 0.77, and 0.39 and 0.54 in Nglanggeran, Girisekar, and Dengok Village, respectively. *wono* in Nglanggeran Village of Batur Agung zone had the highest AGB and AGC, followed by *wono* in Dengok Village of Ledok Wonosari zone, and finally in Girisekar Village of Pegunungan Sewu zone with estimated AGB and AGC values of 210.96 ton ha^{-1} and 99.15 ton C ha^{-1}, 73.58 ton ha^{-1} and 34.58 ton C ha^{-1}, and 57.92 ton ha^{-1} and 27.22 ton C ha^{-1}, respectively. Furthermore, the owners of *wono* require support from a diverse range of interests in order to maintain and expand *wono's* biomass and storage.

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