# TREE VEGETATION AFFECTING SOIL STABILITY, SOIL POROSITY AND SOIL TOTAL NITROGEN IN THE PROTECTED FOREST OF KULON PROGO COMMUNITY FORESTRY, YOGYAKARTA, INDONESIA

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**Abstract.** This research aimed to investigate the influence of tree vegetation on basic soil functions reflected by soil structural stability (SSy), soil porosity (SPy), and soil total nitrogen (STN). Data were collected from 35 plots distributed across five stand types in the protected forest of Kulon Progo Community Forestry, in Yogyakarta, Indonesia. (*Pinus* [PN], *Aleurites-Swietenia* [AS], *Swietenia-Acacia* [SA], *Melaleuca-Acacia* [MA], and *Tectona-Dalbergia* [TD] stands). Comparative analyses were applied to compare SSy, SPy and STN. The influences of tree vegetation and environmental factors on SSy, SPy and STN were evaluated using principal component analysis (PCA) and redundancy analysis (RDA). Our results showed that SSy, SPy and STN varied among plots and stand types where those were directly proportional to each other. Overall, PN stands exhibited less values of basic soil functions than other stands. In this regard, tree vegetation provided high influence on SSy, SPy and STN where the most important factor was an interaction among canopy coverage, soil organic matter and soil organic carbon which are directly proportional to each other and negatively correlated to below-stand utilization. Accordingly, dense-canopy trees are highly recommended for species enrichment by considering adaptive management systems, to ensure the ecological restoration process of degraded forests.
**Keywords:** *soil function, ecosystem-function, restoration, tree vegetation, organic-matter*

## Introduction

Deforestation caused by forest encroachments and illegal-logging results in land degradation leading to the loss of soil function (Veldkamp et al., 2020; Sanji et al., 2020). In basic level, soil function is widely considered as providing understanding on ecosystem or ecological function related to water storage and nutrient cycling (Srivastava and Vallend, 2005; Elsacker, 2011). In this regard, forest holds an important role in providing ecosystem functions through many services such as water and air purification (Song et al., 2016), erosion control (Vatandaşlar et al., 2020), nutrient cycling and soil formation (Foster and Bhatti, 2006; Šamonil et al., 2010). Therefore, afforestation or reforestation could be an effective approach to enhance ecological conditions (Wang et al., 2023). Moreover, the ecological functions then become important keys of ecological success in a reforestation program besides forest structure and composition (Noss, 1990; Ruiz-Jaen and Aide, 2005).

The ecological or ecosystem function is critical in a reforested area, which mean that the restored area is functioning adequately through the rehabilitation or reforestation program (Ruiz-Jaen and Aide, 2005; Munro et al., 2012). As the reciprocal relationship between soil


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and vegetation (FAO, 2015), tree vegetation cover in a reforested area can possibly prevent soil degradation and desertification by maintaining soil function including stabilizing the soil, maintaining water and nutrient cycling (Tongway and Hindley, 2004; Munro et al., 2012) and reducing water and wind erosion (FAO, 2015). Although climate, topography, physical condition and tillage determine the basic soil function, some studies reported that vegetation cover and land use significantly influence the soil condition (Monnier et al., 2015; Jiang et al., 2022; Elsacker, 2011; Udayana et al., 2019; Aji et al., 2021).

One of the crucial roles of forest ecosystem on soil is providing organic materials from leaves, twigs, branches, reproductive organs, etc. (Tandel et al., 2009; Osman, 2013). By providing those organic materials, vegetation cover influences soil structure stability (Monier et al., 2015; Jiang et al., 2022) reflecting soil structure resilience (Reynolds et al., 2009). Moreover, tree vegetation cover will also affect soil porosity (Rahman et al., 2019) due to the high organic matter under the tree cover and rooting pattern (Tandel et al., 2009; Piane et al., 2022). In relation to nutrient cycling, several studies in China showed that forest rehabilitation increases soil organic carbon and soil total nitrogen (Kong, 2019; Dong et al., 2022) by changing the input rate of organic matter and the decomposition (Zhang et al., 2013). Research in West Kalimantan (Indonesia) also showed that afforestation improves SOC, nitrogen and soil pH (Agus et al., 2014).

In the reforested area of the protected forest of Kulon Progo Community Forestry and most areas of Community Forestry in Indonesia, studies related to local basic ecological function are barely concerned and published. Most studies were commonly focused on provisioning service such as ecotourism potential (Dewi et al., 2017; Nuringsih et al., 2019; Ariyani, 2021). In fact, basic soil function is a crucial aspect of a reforested area (Ruiz-Jaen and Aide, 2005; Munro et al., 2012). In this regard, the reforested area of Kulon progo community Forestry would provide important roles for the ecosystem functions restoration due to the limited forest area in the region. The total reforested area was only 856.5 ha, which is about 5% of the total forest area in the Special Territory of Yogyakarta (Aji et al., 2015). Accordingly, as the successful of the reforestation program, about 30% of the reforested area (254.9 ha) was designated as a protected forest in 2007, considering the environmental conditions related to vegetation cover, slope and altitude (Kementerian Kehutanan, 2007). Currently, The Kulon Progo Community Forestry has been one of successful participatory forest rehabilitation stories in Indonesia. However, we still lack of a fundamental understanding on the variation of soil ecological functions in various stand types and how big is the role of tree vegetation on the basic soil ecological functions, given the limited studies on this aspect.

This study aimed to assess the role of tree vegetation and several associated environmental factors on the potential of soil ecological functions characterized by structural stability index, soil porosity and total nitrogen. In this study, the basic soil ecological functions were examined and the main influencing factors were assessed by employing ordination methods. We expected that soil structural stability index, soil porosity and soil total nitrogen would vary as the variation of tree vegetation characteristics and the associated environmental factors.

## Materials and methods

### *Study area*

Study was carried out in the protected forest of Kulon Progo community forestry which is part of reforested area of Kulon Progo state forest located in Kokap Sub-district,


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Kulon Progo Region, Special Territory of Yogyakarta, Indonesia (Siswo et al., 2023a, b). Kulon Progo community forestry is a former damaged forest due to a massive deforestation peaked in 1998 as one of the social impacts of global monetary crisis (Wikipedia, 2022). However, since the 2000s this area has been gradually rehabilitated under social forestry program through community forestry scheme to accommodate conflict of interest between forest development and social need of the local community (Balai KPH Yogyakarta, 2013). Currently, the forest cover is generally a mixed-forest that we have classified into five stand types including *Pinus* (PN), *Aleurites-Swietenia* (AS), *Swietenia-Acacia* (SA), *Melaleuca-Acacia* (MA) and *Tectona-Dalbergia* (TD) (HKm Mandiri, 2022; Siswo et al., 2022, 2023a, b) which is also presented in *Figure 1a-f*.

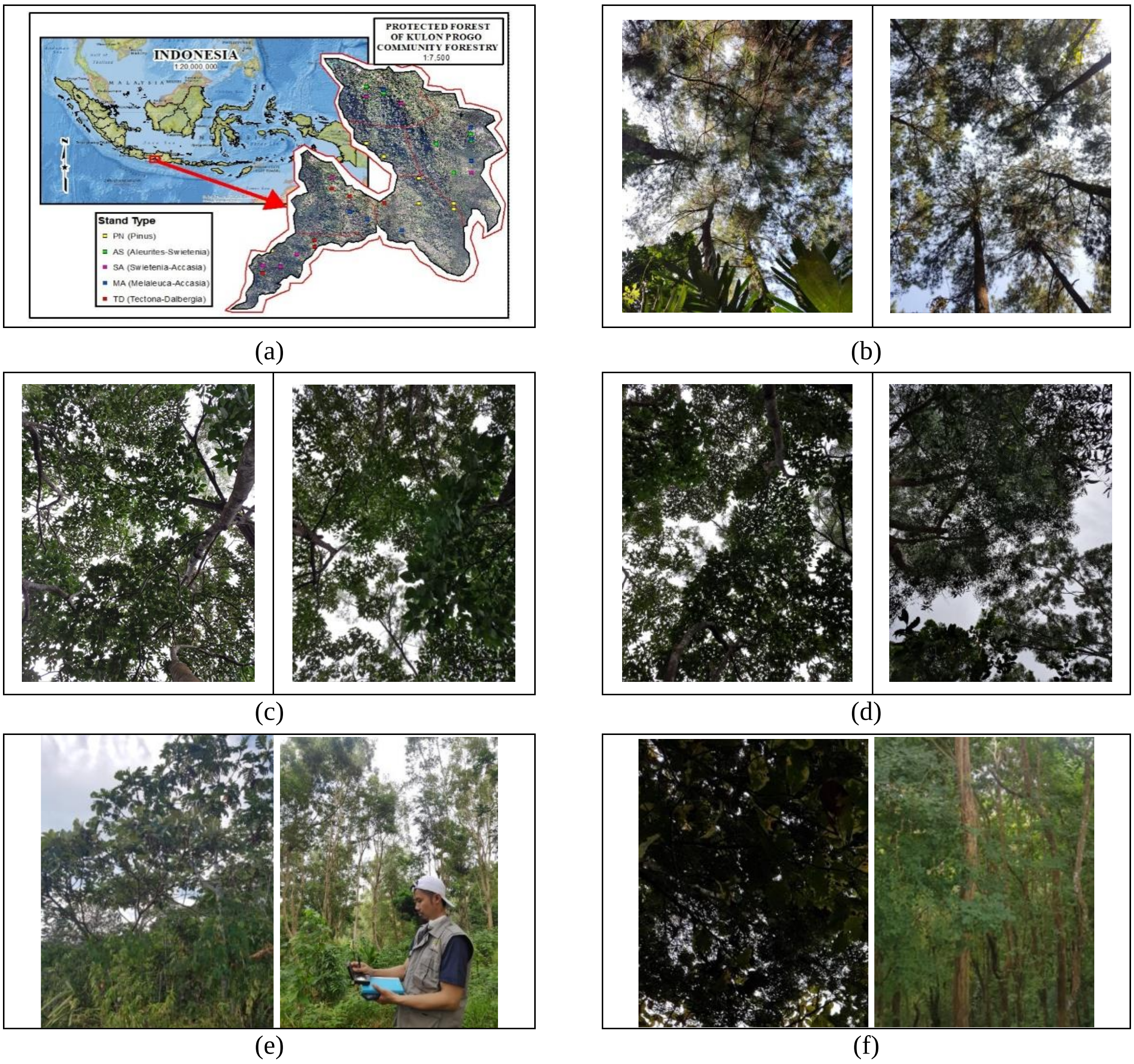


***Figure 1.*** *General description of study area. (a) Map of the sampling area (b) Pinus (PN) stand, (c) Aleurites-Swietenia (AS) stand, (d) Swietenia-Acacia (SA) stand, (e) Melaleuca-Acacia (MA) stand, and (f) Tectona-Dalbergia (TD) stand*

## *Data collection and analysis*

Tree vegetation characteristics and associated environmental factors related to topography, edaphic, and anthropogenic among stand types were assessed. Data


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collection and analysis was carried out from August to September 2022. The data were collected from 35 quadratic plots sized 20 × 20 m which were purposively selected to represent each stand type with seven replications (*Table A1*). Detailed description of the study site, tree vegetation characteristics and the highlighted environmental factors related to topographic, edaphic and anthropogenic can be seen in our previous articles (Siswo et al., 2023a, b). Edaphic data were investigated through soil sampling from the top soil layer as most of the variation in soil properties occurs in this layer, mainly related to the effect of vegetation (Hu et al., 2018; Suyana et al., 2021). Detailed soil sampling and analysis were explained in Siswo et al. (2023a).

We characterized the basic soil ecological function potential by soil structural stability index (SSy), soil porosity (SPy) and soil total nitrogen (STN) including soil total nitrogen concentration (STNc) and soil total nitrogen stock (STNs) to represent soil stability, water infiltration and nutrient cycling, respectively. SSy reflects the ability of soil to resist wind or water erosion, rupture, and disintegration (Deng and Du, 2011; Nwite, 2015). Meanwhile, SPy is associated to infiltration rate (Sun et al., 2018) and water storage or water retention (Batista et al., 2018). Moreover, STN is essential nutrient required by plants in the largest quantity and is important for soil fertility and soil quality (Reeves, 1997), limiting crop productivity (Smil, 1999).

We applied the following formula to calculate soil structural stability (Pieri, 1992) and soil porosity (PPT, 1995):

$$SSy = \frac{\text{soil organic matter}}{\text{clay+silt}}\ x\ 100 \quad \text{(Eq.1)}$$

$$SPy = 1 - \frac{\text{Bulk Density}}{\text{Specific gravity}}\ x\ 100 \quad \text{(Eq.2)}$$

For STN, we included STNc gained from laboratory analysis using Kjeldahl method (Siswo et al., 2023a) and STNs calculated as follow (Zhang et al., 2013):

$$STNs = \text{STN}c \text{ x Bulk Density x Soil Depth (cm) x } 100 \quad \text{(Eq.3)}$$

We analyzed variation of SSy, SPy, STNc and STNs among sample plots by calculating the coefficient variations. We also determined the relationship among these variables by employing correlation analysis. Moreover, we applied a 1-way analysis of variance (ANOVA) followed by a post-hoc test using the Bonferroni method to compare SSy, SPy and STN among stand types. The coefficient variation, correlation analysis and ANOVA were performed in SPSS 25.0.

Influence of tree stand characteristics and other associated factors on the basic soil functions was analyzed using a redundancy analysis (RDA). We used this exploratory pattern association type approach (ordination method) due to the unbalanced nature of many variable combinations in ecological data sets (Rabbi et al., 2014; Hu et al., 2018). We set explanatory variables including vegetation factors (Shannon diversity index, density, basal area, canopy height and canopy coverage), topographic factors (elevation, slope position, slope gradient and bare rock), edaphic factors (pH, BD, clay, sand and silt) and factors related to anthropogenic (below-stand utilization, distance from road and distance from streams). Furthermore, we listed SSy, SPy and STN (STNc and STNs) as the response/dependent variables.


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To run RDA, we preliminary detected *multicollinearity* among explanatory variables using principal component analysis (PCA) as applied by Siswo et al. (2023a). The PCA summarized the explanatory variables based on the *multicollinearity* (Perez, 2017). The number of summarized factor (component) for RDA was determined based on the eigenvalues where the number of variables with ≥ 1 of eigenvalues indicates the number of summarized factor (main component). Meanwhile, the member of each summarized factor (component) could be determined based on the largest correlation between each variable and each factor (component) formed (Beaumont, 2012). Furthermore, we took the score values of the grouped/summarized variables as the explanatory variable in RDA. The RDA was run in PC-ORD 7 (Peck, 2010) while PCA was analyzed in SPSS to earn detail explanation of the grouped variables (Beaumont, 2012).

## Result

### *Between plots variability in soil structural stability, soil porosity and soil total nitrogen*

From total of thirty-five observed plots, our result showed that SSy and SPy in the protected forest of Kulon Progo Community Forestry varied from 1.64% to 6.69% and 27.57% to 54.93%, respectively (average values; 3.58% and 42.81%, respectively) (*Fig. 2a, b*). Meanwhile, STN as a soil function related to nutrient ranged from 0.11% to 0.29% and 2.02 Mg $ha^{-1}$ to 5.35 Mg $ha^{-1}$ for STNc and STNs, respectively (average values; 0.22% and 3.78 Mg $ha^{-1}$ for STNc and STNs, respectively) (*Fig. 2c, d*). The coefficient variations of those investigated basic soil functions were consecutively 35.02%, 14.90%, 23.36% and 24.03% for SSy, SPy, STNc and STNs. Moreover, we also found inter-relationships among these functions as indicated by positive correlations with each other (*Table 1*).

### *Variation of soil structural stability, soil porosity and soil total nitrogen among stand types*

At stand level, our study found significant differences in SSy, SPy and STNs among stand types values, in spite of the similarity in STNc (*Fig. 3a-d*). The PN and MA stands significantly showed lower SSy compared to TD stands. Meanwhile, other stand types including AS and SA stands exhibited the more equal SSy value to TD stand although they were not significantly higher than PN and MA stands. On average, the values of SSy in PN and MA were only 2.89% and 2.96%, respectively. However, MA stand was slightly better than PN stand in terms of SPy and STNs. These two basic soil ecological functions in MA were not only equal to AS and SA but also not significantly different from TD stand which is significantly higher than PN stand. Overall, the average values of SSy, SPy, STNc and STNs in TD stand accounted for 4.90%, 48.89%, 0.24% and 4.34 Mg $Ha^{-1}$, respectively. These values were not only higher than those in the other stand types, but also above the average values of the entire sampling plots which are implied in *Figure 2a-d*.

***Table 1.*** *Correlation analysis among soil stability, soil porosity, soil total nitrogen concentration and soil total nitrogen stock*

| Variables | SSy | SPy | STNc | STNs |
|---|---|---|---|---|
| SSy | - | 0.716** | 0.600** | 0.620** |
| SPy | - | - | 0.547** | 0.564** |
| STNc | - | - | - | 0.951** |
| STNs | - | - | - | - |

SSy = soil stability, Spy = soil porosity, STNC = soil total nitrogen concentration
**Indicates a significant correlation at alpha 0.01, *indicates a significant correlation at alpha 0.05


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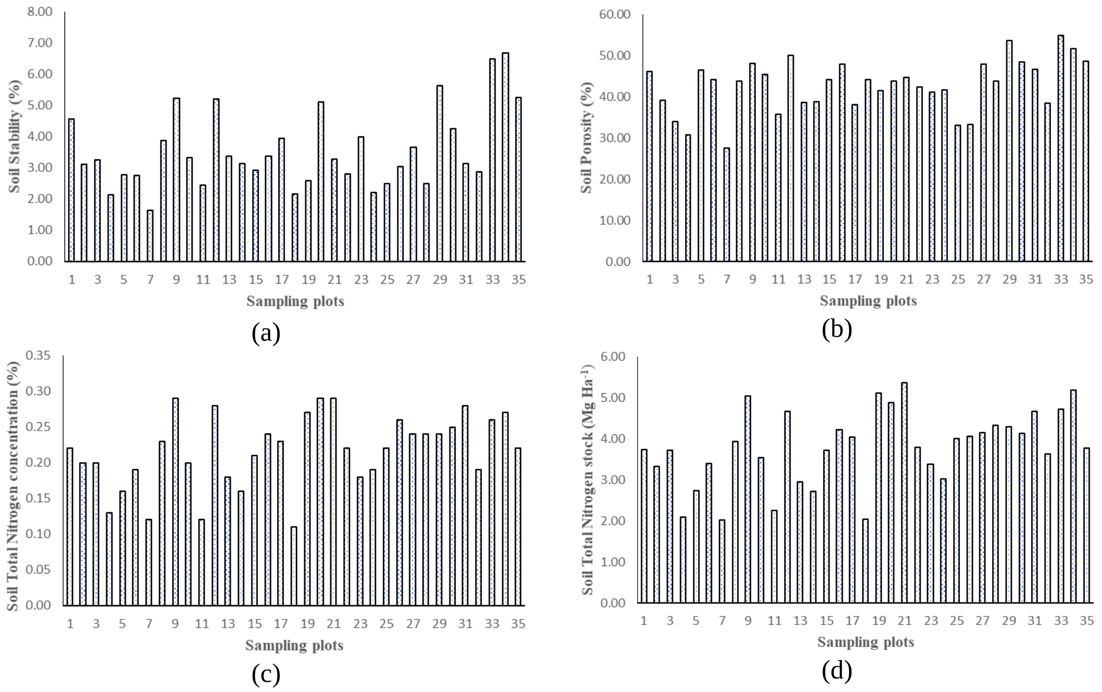


***Figure 2.*** *Between plot variations in SSy (a), SPy (b), STNc (c) and STNs (d) in the protected forest of Kulon Progo Community Forestry. SSy is soil structural stability, SPy is soiol porosity, STNc is soil total nitrogen concentration and STNs is total nitrogen stock*

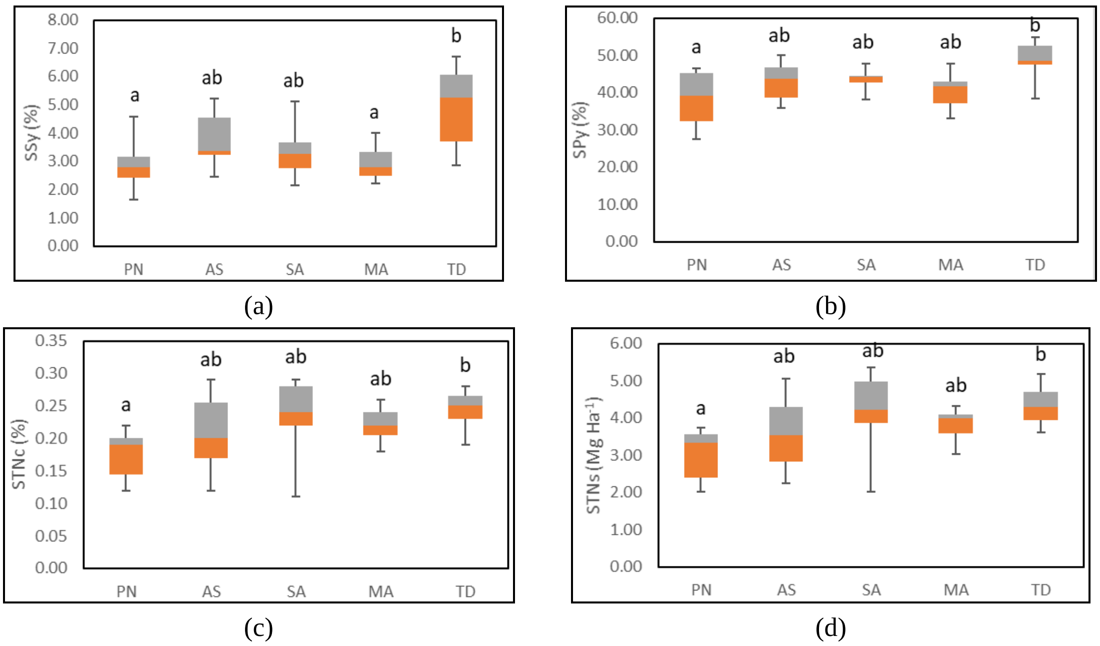


***Figure 3.*** *Variations in SSy (a), SPy (b), STNc (c) and STNs (d) among stand types. Note: Basic soil functions; SSy is soil structural stability, SPy is soil porosity, STNc is soil total nitrogen concentration and STNs is total nitrogen stock. Stand types; PN = Pinus stand, AS = Aleurites-Swietenia stand, SA = Swietenia-Acacia stand, MA = Melaleuca-Acacia stand, TD = Tectona-Dalbergia stand. Yellow and grey areas of the boxes indicate the second and third quartiles, respectively. Whiskers imply the upper and the lower quartile. Different letters (a, b, c) demonstrate significant differences between plot groups (ANOVA, $p < 0.05$)*


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### *Main factors influencing soil structural stability, soil porosity and soil total nitrogen*

Considering the common nature of ecological data which is usually showing inter-correlation (multicollinearity) among predictor variables, PCA summarized the highlighted factors (five tree vegetation factors and another 14) into six factors/components (*Table 2*). Implicit in the PCA results, component 1 consisted of canopy coverage, below-stand utilization, SOM and SOC. In this component, the canopy coverage, SOM and SOC were positively correlated to each other and negatively correlated to below-stand utilization. Component 2 grouped canopy height, altitude, slope position, distance from road and distance from river. In component 2, canopy height was directly proportional to distance from road and indirectly proportional to altitude, slope position, distance from river. Furthermore, component 3 was a grouped factor of diversity index, slope degree and bulk density, by showing positive correlation among each other. Component 4 summarized density and basal area where both factors show negative correlation. Moreover, component 5 was a combination of silt, clay and sand (soil texture), showing that clay is negatively correlated with silt and sand concentration in the composition. Lastly, the sixth component was the mixture factors of bare rock and soil pH, where the two factors influence each other.

***Table 2.*** *Principal component analysis (PCA) loading*

| NO | Variables | PCA component | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | Density | 0.066 | -0.176 | -0.338 | **0.823** | 0.193 | -0.145 |
| 2 | Basal area | 0.129 | 0.065 | 0.128 | **0.850** | -0.165 | 0.277 |
| 3 | Canopy cover (%) | **0.794** | 0.135 | 0.102 | 0.357 | 0.018 | -0.013 |
| 4 | Canopy heigh (m) | 0.110 | **-0.734** | 0.588 | 0.337 | -0.142 | -0.143 |
| 5 | Diversity index | 0.183 | 0.284 | **0.679** | -0.257 | 0.129 | 0.091 |
| 6 | Altitude (masl) | 0.101 | **0.793** | 0.157 | 0.102 | -0.147 | -0.160 |
| 7 | Slope (%) | -0.275 | 0.100 | **0.603** | 0.0.70 | -0.115 | 0.061 |
| 8 | Slope position (topography) | -0.192 | **0.567** | 0.388 | -0.281 | -0.220 | -0.316 |
| 9 | Bare rock (%) | -0.017 | -0.0.95 | -0.101 | 0.049 | 0.148 | **0.785** |
| 10 | Distance from road (m) | 0.070 | **-0.560** | 0.504 | -0.156 | 0.161 | 0.275 |
| 11 | Distance from river (m) | 0.045 | **0.597** | 0.554 | 0.143 | -0.352 | 0.031 |
| 12 | Below-stand utilization | **-0.484** | 0.427 | -0.404 | -0.287 | 0.104 | 0.241 |
| 13 | Soil texture (silt) | 0.331 | -0.220 | -0.004 | 0.434 | **0.680** | -0.196 |
| 14 | Soil texture (clay) | -0.106 | 0.115 | -0.071 | -0.008 | **-0.969** | -0.026 |
| 15 | Soil texture (sand) | -0.203 | -0.070 | 0.107 | -0.454 | **0.668** | 0.247 |
| 16 | SOM | **0.932** | -0.070 | -0.123 | 0.008 | 0.059 | 0.111 |
| 17 | SOC | **0.936** | -0.053 | -0.019 | -0.028 | 0.073 | 0.082 |
| 18 | pH | 0.133 | -0.030 | 0.217 | -0.006 | -0.122 | **0.730** |
| 19 | BD | 0.040 | -0.101 | **0.670** | -0.027 | 0.149 | -0.031 |
| Eigenvalue | | 4.068 | 2.902 | 2.549 | 1.806 | 1.555 | 1.348 |
| Variance explained (%) | | 21.41 | 15.27 | 13.47 | 9.50 | 8.19 | 7.10 |
| Cumulative value of variance explained (%) | | 21.41 | 36.68 | 50.10 | 59.60 | 69.46 | 74.87 |

RDA exhibited the influence of the six components (summarized factors) on SSy, SPy, STNc and STNs. As shown in *Table 3*, the RDA had 27.804, 0.298 and 0.045 of the eigenvalues in the first three axes and showed 65.3% of the total variance explained.


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Based on *Table 3* and *Figure 4*, component 1 showed a strong positive effect on the SSy, SPy, STNc and STNs. Furthermore, component 5 showed strong effect on the soil porosity. Meanwhile, other components showed weak correlations (components 2, 3, 4 and 6). In relation to those relationships, we found that component 1 provided the most dominant influence on the highlighted basic soil functions (*Table 4*; *Figure 4*). Variation partitioning, component 1 contributed more than half of the total variance explained, while the other five components hold only 41.80% of the total variance (*Table 4*).

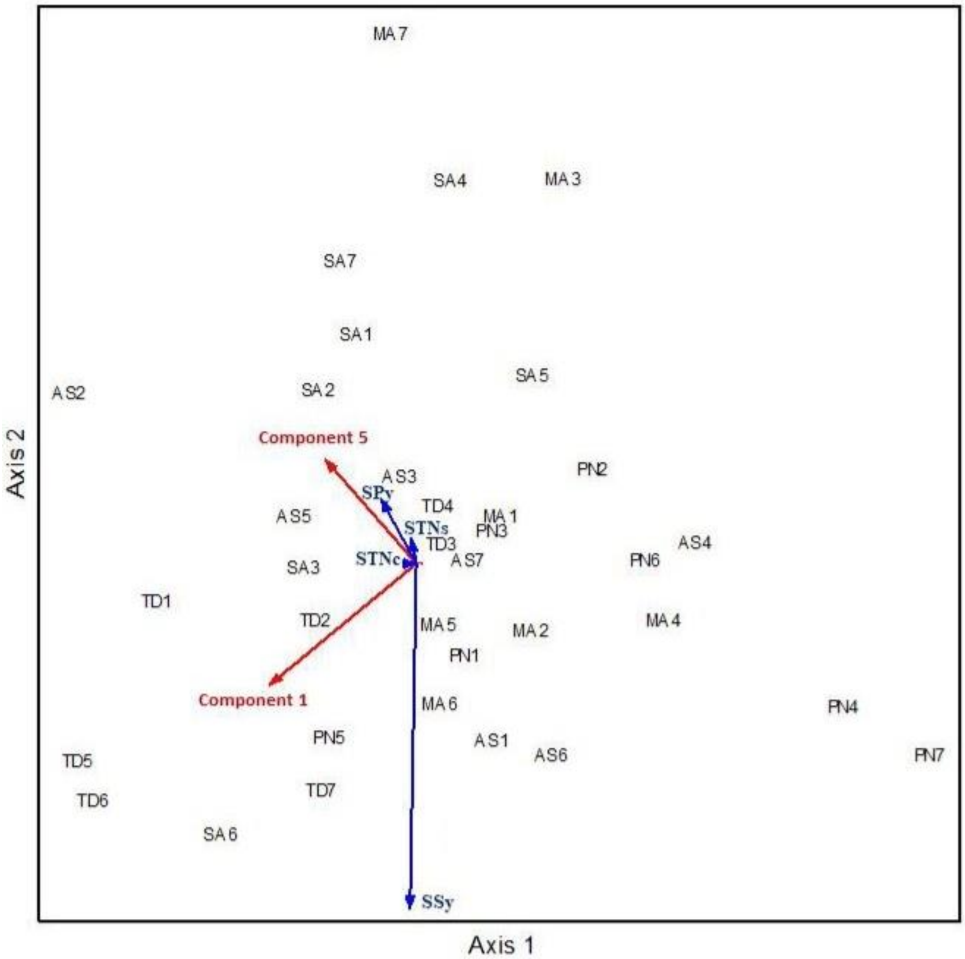


***Figure 4.*** *Effect of tree vegetation characteristics and environmental factors on SSy, SPy, STNc and STNs in the protected forest of Kulon Progo Community Forestry. SSy is soil structural stability, SPy is soil porosity, STNc is soil total nitrogen concentration and STNs is total nitrogen stock*

***Table 3.*** *Summary statistics of redundancy analysis (RDA) between tree vegetation communities and environmental factors*

| Summary statistic | Axis1 | Axis2 | Axis3 |
|---|---|---|---|
| Eigenvalues | 27.804 | 0.298 | 0.045 |
| Variance explained (%) | 64.5 | 0.7 | 0.1 |
| Cumulative explained (%) | 64.5 | 65.2 | 65.3 |
| Pearson correlation | 0.817 | 0.608 | 0.259 |


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***Table 4.*** *Partial variation determining the main influencing factor on soil structural stability, soil porosity and soil total nitrogen*

| Summarized factors | Partial variance explained (%) |
|---|---|
| Component 1 | **38.0** |
| Component 5 | **14.4** |
| Component 6 | **5.3** |
| Component 2 | **3.4** |
| Component 4 | **2.3** |
| Component 3 | **1.9** |

## Discussion

In general, basic soil function in the protected forest of Kulon Progo Community Forestry is not yet fully functional. Soil stability in the protected forest of Kulon Progo Community Forestry was mostly still in degraded condition and high risk of degradation. The average value of <5% soil stability is categorized degraded and the maximum value between 5% and 7% is still classified high risk (Reynolds et al., 2009). Meanwhile, the values of soil porosity ranging from 27.57% to 54.93% are categorized porous to extremely porous and good for plant growth. According to Pagliai (1998), the lower limit soil porosity for good soil is 10% and thus the average values of total porosity > 40% in the study area is categorized extremely porous. For soil nutrient, soil function in this area is relatively good as seen from an average of 0.22% soil total nitrogen concentration and 3.78 tons/ha of total nitrogen stock/content. Overall, STNc and STNs in this area could be categorized as medium, ranging from 0.11% - 0.29%. According to PPT (1995) STNc is low if it is less than 0.1% and high if it is more than 0.3%. With an average STNc of 1.25% in this area (Siswo et al., 2023a), the carbon to nitrogen ratio (c/n ratio) was 6:1 which is often found in arable soils, although this value is still relatively low (PPT, 1995). This was likely related to organic matter supplied by plant residues which generally has a lower c/n ratio resulting in faster decomposition process and tending to release plant-available nitrogen (Munawar, 2011; Hoyle and Fairbanks, 2013; Lesmana, 2019).

Organic material is generally dominant content of the top soil in forest areas (Osman, 2013; Liu et al., 2016). In this study, inter-relationship among the three observed basic soil functions in our study appeared to be related to the organic matter. We found that most of the plots with higher organic matter (Siswo et al., 2023a) had higher SSy, SPy, STNc and STNs (*Fig. 2*) which were directly proportional to each other (*Table 1*). In this regard, soil structural stability relies on soil organic matter as the most prominent binding agents which form stable aggregates (Simansky, 2013). Moreover, the more soil organic matter also means more soil pores and lower bulk density (Cates, 2020) where the pores are supporting a great impact for infiltration (Rahman et al., 2019; Piane et al., 2022). In line to this finding, Dorner et al. (2010) suggested a relationship between soil structure and pore functionality where the destruction of soil structure affects the function of its pores. In addition, proportional relationship of both SSy and SPy to TN (STNc and STNs) was also related to soil organic matter considering that soil organic matter contains nitrogen which is expressed in a carbon-to-nitrogen ratio (Leu, 2012; Hoyle and Fairbanks, 2013).

In relation to different values of SSy, Spy and STN among stand types in current study, our previous paper (Siswo et al., 2023a) confirmed that PN and MA had the lowest values


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of organic carbon and organic matter while TD exhibited the inversed values. This is in line to the low SSy value of PN stand considering that soil organic matter is a great influencing factor for soil structural stability (Simansky, 2013; Monier et al., 2015; Jiang et al., 2022). Meanwhile, the higher proportion of clay in MA stand (Siswo et al., 2023a) might support the higher SPy and STN which were closer to those in AS, SA and TD stands. According to Hillel (2013), clay is finest soil particles having more numerous pores. Correspondingly, STN (STNc) also increased along with its positive relationship to SPy (*Table 2*). Regarding the lower SOM, Siswo et al. (2023a) reported that PN exhibited sparse canopies related to the leaf character of *P. merkusii* as a needle-leaved tree (Backer and Van-den-Bakhuinzen, 1968). In addition, the lower organic matter in MA might be related to the relatively small leaves of *M. leucadendra* (Yudhoyono and Sukarya, 2013) and the low stand density of this species in the entire area of Kulon Progo forest (Balai KPH Yogyakarta, 2013). On the other side, TD stand dominated by *T. grandis* and *D. latifolia* was understandable to have higher organic matter considering the denser and higher canopy supported by the lower intensity of below-stand utilization. Characteristically, *T. grandis* is a broad leaves tree with wide canopy (Backer and Van-den-Bakhuinzen, 1968; Yudhoyono and Sukarya, 2013), and *D. latifolia* has a large, dome-shaped canopy with lush green leaves (Yudhoyono and Sukarya, 2013).

Overall, vegetation cover in the study site held an important role on the highlighted basic soil functions. RDA proved the effect of tree vegetation characteristic and some associated factors on the variation of SSy, SPy and STN discussed above. The six grouped explanatory variables (component) listed in *Table 4* significantly determined the observed basic soil functions (SSy, SPy, STNc and STNs) and satisfactorily explained the variation with 65.3% of total variance explained (*Table 4*). Component 1 (positive interaction factors of canopy height, soil organic matter and soil organic carbon which are indirectly proportional to below-stand utilization) exhibited the highest contribution indicating that these variables are the most important factors for the SSy, SPy and STN in this study. Correspondingly, previous report (Siswo et al., 2023a) has revealed that soil organic matter and soil organic carbon increased with the increase of canopy coverage which were positively correlated to canopy height and inversely proportional to below-stand utilization. Our finding matched the common recognition that optimum canopy contributes to many important functions by modifying the micro environmental conditions of the forest related to the forest canopy ability to control the incoming light, wind, rainfall and temperature (Lowman and Rinker, 2004). According to Nakdarni et al. (2013), forest canopy is important for forest functioning, diversity and ecological resilience. Moreover, trees having dense canopy with low intensity of below-stand utilization will reduce the risk of soil erosion (Devi, 2021) from the direct impact of raindrops (Zhang et al., 2013; Hu et al., 2018). In turn, it will provide a good advantage to increase the supply of SOC/SOM by accumulating litter and understory cover (Roose et al., 2006; Wang et al., 2011). The increasing SOC leads to the increase of soil stability (Monier et al., 2015; Jiang et al., 2022; Hoyle and Fairbanks, 2013; Simansky, 2013), soil porosity (Rahman et al., 2019; Cates, 2020; Piane et al., 2022) and soil fertility (Lv et al., 2022).

Other components provided smaller contribution to affect SSy, Spy, and STN where only component 5 showed the significant effect, mainly for soil porosity, with contribution of more than 10% of variance explained (*Table 4*; *Fig. 4*). Indeed, soil texture (component 5) basically determines soil porosity (Phogat et al., 2015) where fine soil has smaller particles but more numerous pores than a coarse soil and vice versa (Hillel, 2013). However, soil texture in our study area was relatively similar to the


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balanced composition of sand, silt and clay called "loam" soil (Siswo et al., 2023a, b) resulting in relatively small variation of the soil texture and its effect on soil porosity. Organic matter might improve some spots with coarse soil approaching the pore level of the finer soil because the accumulation of organic matter is able to modify soil stability and porosity (Tandel et al., 2009; Cates, 2020; Piane et al., 2022). Moreover, other vegetation characteristics and all the observed associated environmental factors summarized in component 2, 3, 4 and 6 had smaller variations and provided only small contribution to affect SSy, Spy and STN. Reported in our previous paper (Siswo et al., 2023a), canopy height, density, diversity index, altitude, slope position, bulk density, soil pH, distance from road and distance from river only showed small ranges.

## Conclusion

In general, reforested area of the protected forest of Kulon Progo Community Forestry showed positive impacts on the ecosystem or ecological function. The highlighted basic soil functions including soil stability, soil porosity and soil total nitrogen showed a close relationship to tree vegetation characteristics and its associated factors. Greater soil stability, soil porosity and soil total nitrogen were found in *Tectona-Dalbergia* stand which is having denser canopy coverage. Inversely, the lower values were explored in the stands with sparser canopy, mainly *Pinus stand*. Moreover, RDA confirmed that in relatively small variation of topographic factors in our study, component 1 (interaction factor of canopy cover, soil organic matter and soil organic carbon which are directly proportional to each other and negatively correlated to below-stand utilization intensity) was the most determining factor for soil structural stability, soil porosity and soil total nitrogen. In clearer words, our result suggested that the denser canopy coverage as the decrease in below-stand utilization, the higher the soil organic matter and soil organic carbon, which further determined the level of soil stability, soil porosity and soil total nitrogen.

Based on the current findings, we conclude that tree vegetation through canopy coverage and organic materials from leaves, twigs, branches, flowers, fruits/seeds and roots could be accurate predictors of ecological function in a restored vegetation. Therefore, improvement of canopy coverage through planting dense-canopy trees and layering modification is highly suggested. In addition, in case of below-stand utilization is inevitable due to the local people's dependence on forest resources, an adaptive management should be carefully considered. To enrich this finding, more study in other reforested areas with various environmental conditions was highly recommended.

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## APPENDIX

***Table A1.*** *General information of sample plots*

| Stand type | Plot no | GPS coordinate | | Dominant species | Average canopy cover (%) |
|---|---|---|---|---|---|
| | | X | Y | | |
| PN | PN1 | 110.133 | -7.80682 | Pinus merkusii | 68.43 |
| | PN2 | 110.132 | -7.80599 | | |
| | PN3 | 110.137 | -7.80981 | | |
| | PN4 | 110.135 | -7.80981 | | |
| | PN5 | 110.126 | -7.81265 | | |
| | PN6 | 110.135 | -7.80823 | | |
| | PN7 | 110.137 | -7.81016 | | |
| AS | AS 1 | 110.133 | -7.80287 | Aleurites molucana, Swietenia macrophylla | 75.50 |
| | AS 2 | 110.132 | -7.80245 | | |
| | AS 3 | 110.132 | -7.80315 | | |
| | AS 4 | 110.136 | -7.80605 | | |
| | AS 5 | 110.137 | -7.80789 | | |
| | AS 6 | 110.138 | -7.80588 | | |
| | AS 7 | 110.138 | -7.80543 | | |
| SA | SA 1 | 110.134 | -7.80347 | Swietenia macrophylla, Accacia auriculiformis, Tectona grandis, Dalbergia latifolia | 74.29 |
| | SA 2 | 110.13 | -7.80817 | | |
| | SA 3 | 110.132 | -7.80305 | | |
| | SA 4 | 110.128 | -7.81299 | | |
| | SA 5 | 110.127 | -7.81375 | | |
| | SA 6 | 110.126 | -7.81368 | | |
| | SA 7 | 110.138 | -7.80786 | | |
| MA | MA 1 | 110.131 | -7.81032 | Melaleuca leucadendra, Accacia auriculiformis | 59.71 |
| | MA 2 | 110.132 | -7.8108 | | |
| | MA 3 | 110.138 | -7.80711 | | |
| | MA4 | 110.134 | -7.81151 | | |
| | MA 5 | 110.133 | -7.80263 | | |
| | MA 6 | 110.138 | -7.80573 | | |
| | MA 7 | 110.138 | -7.80505 | | |
| TD | TD 1 | 110.13 | -7.80886 | Dalbergia latifolia, Tectona grandis | 85.43 |
| | TD 2 | 110.132 | -7.80922 | | |
| | TD 3 | 110.131 | -7.80935 | | |
| | TD 4 | 110.129 | -7.8121 | | |
| | TD 5 | 110.129 | -7.81251 | | |
| | TD 6 | 110.126 | -7.81417 | | |
| | TD 7 | 110.133 | -7.80975 | | |

Stand types: *Pinus* stand (PN), *Aleurites—Swietenia* stand (AS), *Swietenia-Accacia* stand (SA), *Meulaleuca-Swietenia* stand (MA), *Tectona-Dalbergia* stand (TD)


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