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Impact of *Michelia champaca* and *Tectona grandis* mono-species and their mixed plantation on chemical soil properties in a tropical semi-evergreen forest

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Abstract Understanding the effects of planted forests on soil properties is of great importance to meet increasing demands for wood production and contributing to forest ecosystem services and soil carbon sequestration. However, the influence of mono- and mixed tree plantations on soil chemical properties remains incompletely explained, particularly in tropical semi-evergreen forests. In this study, a mono-plantation of *Michelia champaca* and *Tectona grandis*, as well as their mixed plantation, were studied on soil variables (pH, SOC, N, P, K) at different depths (0-10, 10-20, and 20-30 cm) in tropical semi-evergreen forest of the Khadimnagar National Park, Bangladesh. All examined pedovariables showed no significant differences among plantation types, notably in the surface soil layer (up to 10 cm). However, significant oscillations were found in the deepest soil layer (20-30 cm), where *M. champaca* and mixed-species plantations obtained the lowest SOC (0.55-0.66%) and N (0.05-0.06%) concentrations. In the intermediate soil layer (10-20 cm) K concentrations were the lowest in *M. champaca* (19.6 mg/kg) and mixed-species plantation (17.6 mg/kg), while *T. grandis* recorded the highest K concentration (27.4 mg/kg). Additionally, the results indicated an increase in pH with soil depth (from 5.30 in the topsoil to 7.00 in the deepest layer), with *T. grandis* showing the lowest values across examined soil layers (5.76-5.95) and significantly differing from *M. champaca*, which exhibited the highest pH over the soil profile (6.29-6.51). Such results suggest the leaching of basic cations (Ca^{2+}, Mg^{2+}, K^+) over the soil profile due to pronounced monsoon rainfalls. Further research is necessary to fully elucidate underlying mechanisms behind the observed impact of examined plantations on chemical soil variables. Considering other variables such as litter chemical composition and various physical and microbiological soil properties can offer valuable guidelines for enhancing more sustainable management of a tropical semi-evergreen forest, prone to soil acidity and water erosion.

Keywords: soil properties, tree species identity, species additive effects, monoculture, mixed culture, soil organic carbon.

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Introduction

Plantation, a significant element of land-use changes in the tropics (Szulecka et al. 2014), has been incorporated into the global forest management principles for meeting the demand of increasing domestic and industrial wood production (O'Brien & Bringezu 2017), and contributing to ecosystem services and soil carbon sequestration (Rahman et al. 2021). Namely, forest plantations currently provide ~1/3 of the total industrial roundwood globally, with projections indicating their potential to contribute to 1/2 of the global industrial roundwood production by 2040 (Liu et al. 2018). Moreover, recent studies reveal that non-wood forest products have played a crucial role in enhancing the well-being of approximately 1.6 billion people worldwide over the past few decades, notably in developing countries such as Bangladesh, contributing to general livelihood aspects, food security, healthcare, nutrition, and various socio-cultural ecosystem services (Ara et al. 2021, Rahman et al. 2021). Having a potential role on soil nutrient dynamics and atmospheric carbon sequestration (van Dijk & Keenan 2007, Paletto et al. 2017, Waring et al. 2020, Valladares-Samperio & Galicia-Sarmiento 2021), plantations on abandoned lands are being promoted and the global coverage of intensively managed plantation forests exceeded 131 million ha with a very high and rapid expansion rate in South Asia (FAO 2020).

Managing sustainable soil fertility in the form of accelerating land-use conversion into plantations has become a growing concern among the scientific communities since it has the implication of plant growth and productivity (Liao et al. 2012, Danise et al. 2021, Panfilova et al. 2022). Tree plantation can influence soil properties, including soil organic carbon (SOC), nutrient content or pH reaction (Zheng et al. 2017, Wu et al. 2021, Hou et al. 2019). In addition, it is well known that plant species can influence soil properties through the absorption of water and nutrients from the soil by their root systems and the replenishment of various soil layers with biomass (Prescott & Vesterdal 2013, Dincă et al. 2018, Wang et al. 2022). Several studies, including those by Onet et al. (2016), Liu et al. (2018), Gao et al. (2021), Stefanowicz et al. (2021) and Li et al. (2021), have confirmed that the selection of tree species and effective plantation management, whether through mono- or mixed-cropping, is crucial for optimizing the aforementioned ecosystem services.

Plantation studies have confirmed that tree species identity and diversity can influence soil properties differently (Sprenger et al. 2013, Dawud et al. 2016), and different results have been recorded from temperate and boreal forests (Prescott & Vesterdal 2013, Walkiewicz et al. 2021). Each mono-species plantation may have its own influencing trait on soil properties; therefore, determining species identity effects on soil properties using mono-species plantation can be straightforward by avoiding inherent soil variability (Brechet et al. 2009, De Long et al. 2019). However, complexities arise when quantifying plantation effects of species mixtures on soil properties. Several studies, including those by Guckland et al. (2009), Dawud et al. (2016), Gong et al. (2021), and Osei et al. (2021), have indicated the positive influence of species diversity on SOC, C/N ratio, and soil pH. Conversely, some studies, such as Schmidt et al. (2015), demonstrated no effects on plant-available N content in the soil of mono-species plantations compared to mixed-species plantations. In addition, it was demonstrated that the species identity effects are not additive, and that species-specific effects disappear in mixed plantation (Murphy et al. 2008). Thus, our understanding of how different species and plantation practices (e.g., either mono or mixed cropping) impact soil properties in forest ecosystems are still not fully explained (Richards et al. 2010), notably in non-nitrogen-fixing mixtures (Liu et al. 2018) and tropical ecosystems.

In this study, we aimed to investigate how mono- and mixed-cropping of two major plantation species impact soil properties in a tropical semi-evergreen forest of significant biodiversity importance, the Khadimnagar National Park (KNP) in Bangladesh. It was hypothesized that both mono-species and mixed-species plantation, attributed to distinct ecophysiological properties (e.g., deciduous vs evergreen specie), can influence SOC and macro-nutrients (N, P, K) content, as well as soil pH reaction. We separately tested above-mentioned soil properties from i) two different mono-species (evergreen *Michelia champaca* and deciduous *Tectona grandis*) and ii) their mixture plantation sites at KNP, which is under restoration by active plantation activities since the 1960s. The recent study has indicated that approximately one-fourth of KNP (nearly 500 ha) still represents vulnerable hilly areas, consisting of grasses and fodders (Rahman et al. 2021), suggesting a potential area for reforestation. Recognizing reforestation as a vital strategy in mitigating climate change (Rai et al. 2021), we believe that this study will not only provide crucial insights for more sustainable forest management in KNP (through optimized mono-/mixed plantation selection), but also make a significant contribution to enhanced soil carbon sequestration (a crucial mechanism for mitigating climate change) on designated reforestation sites in KNP and similar evergreen ecosystems.

Materials and Methods

Site description

This local-scale study was conducted at the Khadimnagar National Park (KNP) under the Sylhet Forest Division of the Bangladesh Forest Department (Figure 1). It is a reserved forest area which has been declared as the National Park in 2006 under the Wildlife Preservation Act 1974 (Redowan et al. 2016). The site location lies between 24°56´-24°58´N latitude and 91°55´- 91°59´E longitude, encompassing 679 ha of dominantly forest area (Figure 1), surrounded by tea gardens (Sobuj & Rahman 2011). The study site falls into the tropical evergreen and semi-evergreen biogeographic zone, and the forest is categorized as the tropical semi-evergreen forest that comprises hillock, known as *Tilla*. The hills are usually low, with an average altitude between 10-50

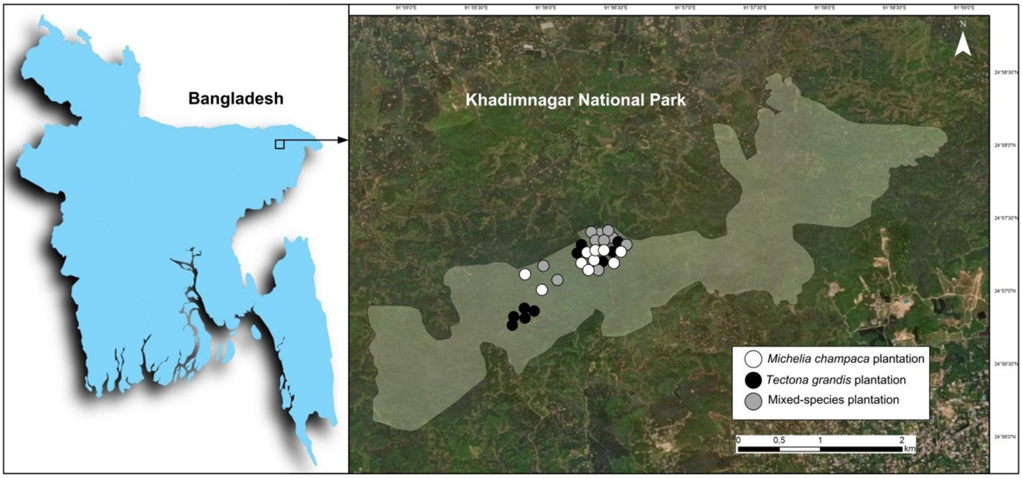

Figure 1 Spatial distribution of the soil sampling locations in the Khadimnagar National Park (KNP), Bangladesh (shapefile source: UNEP-WCMC, 2023).

m (Rahman et al. 2021), gently sloping, and drained by the many watersheds, known as Chara (BBS 2005, Ghose et al. 2017).

Typical pedological conditions are characterised by acidic Ultisols (IUSS Working Group WRB 2022), with textures ranging from clay loams to pale brown clay loams on the hills (Chowdhury et al. 2004, Sobuj & Rahman 2011). The climate is warm and humid, characterized by the tropical monsoon, with the average maximum temperature of 30.7°C (April-May), and the average minimum temperature of 18.9°C (December-January). Annual rainfall averages 3931 mm, with the majority occurring between June and September (BBS 2017).

Tree Species of Khadimnagar National Park

The KNP has a distinct characteristic of tropical semi-deciduous forest with evergreen understory vegetation (IPAC 2009). The natural part of the KNP was comprised of natural bamboos which were gradually fallen and converted into plantations throughout the 1960s (IPAC 2009). Different mono- and mixed- tree species plantations started in 1954 and continued until 2004; thus, the forest has been converted to a semi-natural state. In the field study by Sobuj & Rahman (2011) have recorded a total of 74 plant species present in the KNP; where 26 were tree species, 17 were shrubs and 31 species were herbs. Major long-rotation plantation species such as *Tectona grandis*, *Artocarpus chapalasha*, *Michelia champaca*, *Dipterocarpus turbinatus*, *Shorea robusta*, *Syzygium grande*, etc., were introduced since the early 1960s. However, some short-rotation speedy developing tree species (e.g., *Acacia auriculiformis*, *Acacia mangium*, *Chickrassia tabularis*) were also introduced since the 1990s. Among the 26 tree species of the KNP, *T. grandis* and *M. champaca* are the two major plantation species, having the highest relative dominance of 37.3% and 10.9%, respectively, with the highest density (3.03/100 m^2) and frequency (77%) valid for *T. grandis* (Sobuj & Rahman 2011).

Soil sampling and laboratory analysis

Soils were collected from i) two different mono-species of *M. champaca* and *T. grandis*, and ii) their mixture plantation in KNP (Figure 1). The selected plantation sites comprised primarily the major dominant and highly abundant tree species of the forest. A total of 30 random study locations of the entire study area, 10 in each of the three different plantation sites, were selected for sampling (Figure 1). The depth of the litter layer at each location was assessed using a meter scale, employing three horizontal measurements at each site, and the average of these measurements was subsequently calculated (Rahman et al. 2022). Then, at each sampling location per one pedological soil profile was opened with a shovel, and soil samples were collected with a soil corer (Φ 50.46x50 mm) over the soil profile following standard pedological procedures and methodology (Ondrasek et al. 2023). In brief, using a 5-point sampling method, profiles were sampled from the fixed depth (0-10, 10-20, and 20-30 cm), cleaned (from stones, root fragments), crushed and sieved (Φ 2 mm) to be finally blended into one composite sample from the fixed depth (Zheng et al. 2017, Ondrasek et al. 2023). Such prepared samples were air dried and subjected to analyses in the laboratory of Soil Resource Development Institute (SRDI), Bangladesh.

The SOC concentration was determined by the Walkley-Black method (Walkley & Black 1934, Aregahegn 2020). The total N concentration was determined by the Kjeldahl method (Khee 2001). Available P was measured following the procedure as described in Ara et al. (2018) by mixing 25 ml of extract solution (0.03 M NH_4F and 0.1M HCl) with 3.5 g of the sampled soil, and further determined by measuring the absorbance on a UV-Vis spectrophotometer (Messtechnik GmbH, Vienna, Austria) at 890 nm. The available K was firstly extracted from 2.5 g of sampled soil by adding 25 ml of 1 M ammonium acetate (CH_3COONH_4), and then the K^+ concentrations of the filtered solution were measured by the flame photometry (Flame Photometer, Models PFP7 & PFP7/C, Cole-Parmer, UK). The pH (KUOSI, FE28-standard) was measured in 0.01 M KCl using a soil-solution extraction ratio of 1:2.5.

Statistical data analyses

All recorded data underwent a normality test using the Shapiro-Wilk test, and the equality of variances was assessed through Levene's test. To evaluate the statistical significance of differences in mean values among the examined tree species and the soil variables (SOC, N, P, K, and pH), an analysis of variance (ANOVA) was performed, followed by Tukey's HSD test at a significance level of $p \leq 0.05$. Complete statistical data analyses were performed in SAS, version 9.4.

Results

Overview of the measured soil properties

The summary statistic of all measured soil properties for the entire study area is given in Table 1. The litter layer remained unaffected by the examined plantation type (data not shown). The determined SOC, N, P and K concentrations were higher in the topsoil layer (0-10 cm) and decreased towards the deeper soil layers, regardless of the type of planting and species identity. The mean SOC concentration of all profiles of the entire study area was 1.02% (ranged from 0.06% in the deepest soil layer to 5.22% in the surface soil layer), total N averaged 0.09% (ranged from 0.00% in the deepest soil layer to 0.42% in the surface soil layer), available P concentration averaged 1.86 mg/kg soil (ranged from 0.48 mg/kg soil in the intermediate soil layer to 3.44 mg/kg soil in the surface soil layer), and the available K concentration averaged 23.85 mg/kg soil (ranged from 7.82 mg/kg to 89.93 µg/g soil in the deepest to the surface soil layers, respectively) (Table 1). In contrast, soil pH increased with depth in all samples, with the mean pH for the studied area of 6.16, and varied from 5.30 in the topsoil to 7.00 in the deepest layer (Table 1).

Table 1 Summary statistics of the measured soil properties (soil organic carbon - SOC, total nitrogen - N, available phosphorous - P, available potassium - K) in the study area (n=30).

Variables	Soil depth	Min.	Max.	Av.	SD
SOC (%)	0 - 10 cm	0.23	5.22	1.35	0.88
	10 - 20 cm	0.09	2.18	1.00	0.52
	20 - 30 cm	0.06	1.59	0.71	0.34
SOC (overall)	**0 - 30 cm**	**0.06**	**5.22**	**1.02**	**0.67**
N (%)	0 - 10 cm	0.02	0.42	0.12	0.07
	10 - 20 cm	0.01	0.18	0.09	0.04
	20 - 30 cm	0.00	0.15	0.07	0.03
N (overall)	**0 - 30 cm**	**0.00**	**0.42**	**0.09**	**0.05**
P (mg/kg soil)	0 - 10 cm	1.44	3.44	2.13	0.49
	10 - 20 cm	0.48	2.70	1.81	0.53
	20 - 30 cm	0.89	2.40	1.65	0.42
P (overall)	**0 - 30 cm**	**0.48**	**3.44**	**1.86**	**0.52**
K (mg/kg soil)	0 - 10 cm	11.73	89.93	31.67	40.63
	10 - 20 cm	7.82	54.74	21.11	24.18
	20 - 30 cm	7.82	50.83	18.77	22.35
K (overall)	**0 - 30 cm**	**7.82**	**89.93**	**23.85**	**20.52**
pH	0 - 10 cm	5.30	6.80	6.05	0.46
	10 - 20 cm	5.30	6.90	6.17	0.49
	20 - 30 cm	5.40	7.00	6.26	0.40
pH (overall)	**0 - 30 cm**	**5.30**	**7.00**	**6.16**	**0.45**

Note: Min.: minimum, Max.: maximum, Av.: average, SD: standard deviation.

Tree species plantation effects on soil properties

Separate and additive effects from two dominant mono species, *M. champaca* and *T. grandis,* and their mixed plantation on chemical soil properties (SOC, N, P, K, and pH) were assessed and compared over the soil profiles. The total SOC, total N, available P and K concentration were the highest within the topsoil (0-10 cm) layer, and followed a decreasing trend with increasing soil depth, in either mono-species or mixed-species plantations (Table 2, Figures 2, 3, 4, 5). However, the average concentration

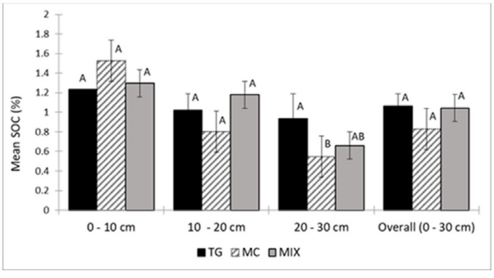

Figure 2 Impact of mono- (*T. grandis* - TG; *M. champaca* - MC) and mixed (MIX) plantation type on soil organic carbon (SOC) concentration. Bars with a different capital letter are significantly different (p<0.05).

of SOC, total N, available P, and K for the overall soil profiles did not vary significantly among plantation sites. Namely, the variations were only significant to some extent and rather limited to the specific deeper soil layers. Different plantations have significantly influenced the accumulation of SOC (p=0.025) and the total N concentration (p=0.008) in the deepest soil layer (20-30 cm), and available K concentration (p=0.042) in the intermediate (10-20 cm) soil layer (Table 2). However, no significant effects (p>0.05) of tested plantation types on available P concentration in the soil layers were found (Table 2). Additionally, the results indicated an increase in pH reaction with soil layer depth, showing significant differences (p<0.05) among the plantation sites (Table 2, Figure 6).

Table 2 Impact of mono- and mixed plantation type on examined pedovariables. Means with a different letter in a column are significantly different (p < 0.05).

Soil Properties	Soil depth	*TG* p.	*MC* p.	Mix p.	p	F value
SOC (%)	0 - 10 cm	1.23a	1.53a	1.30a	0.747	0.295
	10 - 20 cm	1.02a	0.80a	1.18a	0.272	1.368
	20 - 30 cm	0.93a	0.55b	0.66ab	**0.025**	**4.243**
SOC (overall) (%)	0 - 30 cm	1.06a	0.83a	1.04a	0.203	1.694
N (%)	0 - 10 cm	0.12a	0.13a	0.12a	0.908	0.097
	10 - 20 cm	0.09a	0.08a	0.11a	0.248	1.469
	20 - 30 cm	0.09a	0.05b	0.06b	**0.008**	**5.784**
N (overall) (%)	0 - 30 cm	0.11a	0.09a	0.10a	0.611	0.502
P (mg/kg soil)	0 - 10 cm	2.29a	2.01a	2.08a	0.431	0.869
	10 - 20 cm	1.85a	1.75a	1.83a	0.916	0.088
	20 - 30 cm	1.57a	1.79a	1.60a	0.459	0.801
P (overall)	0 - 30 cm	1.90a	1.86a	1.84a	0.896	0.110
K (mg/kg soil)	0 - 10 cm	31.98a	35.58a	29.98a	0.776	0.256
	10 - 20 cm	27.37a	19.59ab	17.59b	**0.042**	**3.586**
	20 - 30 cm	23.59a	16.79a	17.19a	0.159	1.972
K (overall)	0 - 30 cm	27.65a	24.07a	21.59a	0.302	1.253
pH	0 - 10 cm	5.76b	6.29a	6.10ab	**0.029**	**4.062**
	10 - 20 cm	5.89b	6.45a	6.17ab	**0.031**	**3.968**
	20 - 30 cm	5.95b	6.51a	6.32a	**0.003**	**7.423**
pH (overall)	0 - 30 cm	5.87b	6.41a	6.20ab	**0.009**	**5.676**

Note: TG: *T.grandis*; MC: *M. champaca*; p: plantation; Mix: Mixed-species plantation; F: F value

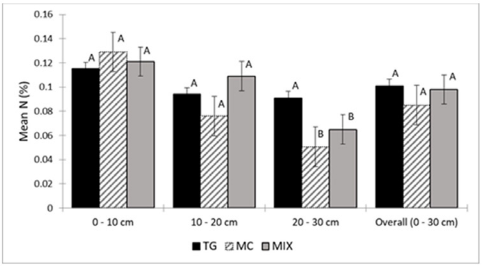

Figure 3 Impact of mono- (*T. grandis* - TG; *M. champaca* - MC) and mixed (MIX) plantation type on total soil N concentration. Bars with a different capital letter are significantly different (p<0.05).

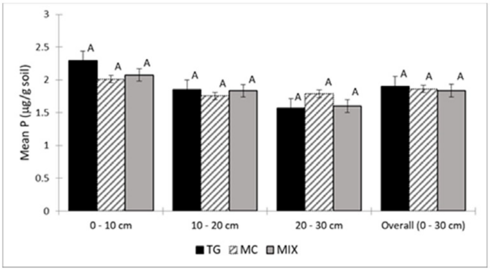

Figure 4 Impact of mono- (*T. grandis* - TG; *M. champaca* - MC) and mixed (MIX) plantation type on available P concentration. Bars with a different capital letter are significantly different (p<0.05).

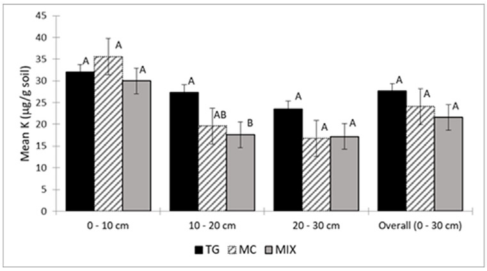

Figure 5 Impact of mono- (*T. grandis* - TG; *M. champaca* - MC) and mixed (MIX) plantation type on available K concentration. Bars with a different capital letter are significantly different (p<0.05).

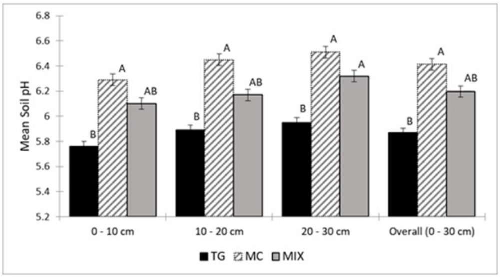

Figure 6 Impact of mono- (*T. grandis* - TG; *M. champaca* - MC) and mixed (MIX) plantation type on soil pH reaction. Bars with a different letter are significantly different (p<0.05).

Tree species-s pecific effects on soil properties in mono-species plantations

Tectona grandis in comparison to *Michelia champaca* mono plantation and their mixed-species plantation has recorded the highest average SOC, total N, available P, and K concentration over the entire (0-30 cm) soil profile; however, these differences were not significant (Table 2). Similarly, in the topsoil layer (0-10 cm) of *M. champaca* plantation, relatively higher SOC (1.53%), total N (0.13%), and available K (35.58 mg/kg) concentration, compared to *T. grandis* (SOC = 1.23%, N = 0.12%, K = 31.98 mg/kg soil) or mixed-species plantation (SOC = 1.30, N = 0.12%, K = 29.98 mg/kg soil) were not significantly different. However, available P concentration in the topsoil of *T. grandis* plantation (2.29 mg/kg) was relatively higher than in *M. champaca (*2.01 mg/kg). In terms of soil pH reaction, *T. grandis* exhibited the lowest values across examined soil layers (5.76-5.95), significantly different from *M. champaca* plantation, with the highest pH over the soil profile (6.29-6.51), but without significant difference from the mixed-species plantation (6.17-6.32) (Table 2).

Species additive effects on soil properties in mixed-species plantations

We observed oscillations in the average SOC concentration and nutrients deposition while comparing mono-species plantations with mixed-species plantation, although the changes were significant only at the specific soil depth. For instance, differences in SOC and total N concentration among the plantation sites were not significant in the surface (0-10 cm) and intermediate (10-20 cm) soil layers, then only in the deepest soil layer (20-30 cm) (Figure 2 and 3). However, the mixed species plantation has increased the average SOC (1.044%) and the total N (0.098%) concentration in comparison to *M. champaca* plantation (SOC 0.827% and total N 0.085%) (Table 2, Figures 2, 3). We did not find any significant differences in available P concentration among the plantation sites (Table 2, Figure 4). However, mixed-species plantation recorded the lowest soil K concentration (17.59 mg/kg) in the intermediate (10-20 cm) soil layer (Table 2, Figure 5).

Discussion

Tree species identities have shown limited impacts on overall soil properties and nutrient distribution within and among the soil layers. In addition, mixed-species plantation had minimal impacts on the majority of examined chemical properties across the soil profile in surveyed locations within KNP. Although the average SOC concentrations across complete soil profiles (0-30 cm) were not statistically different among the studied plantation types, an exception was found in the deepest soil layer (20-30 cm), where *T. grandis* mono-species and mixed-species plantation obtained the highest SOC concentration, in contrast to *M. champaca* mono-species plantation with the lowest SOC concentration (Table 2, Figure 2). Our findings align with recent observations conducted in the Jaldapara National Park, situated in the Indian Eastern Himalayan region, where SOC content exhibited significant variation only within the surface (0-20 cm) soil layer across five distinct forest stands, which encompassed species such as *T. grandis* and *M. champaca* (Rai et al. 2021). Similarly, a recent study conducted over the same area of KNP found no correlation between tree species distribution and soil organic matter, attributing these results to the loss of organic matter caused by water erosion, especially during heavy rainfall in the monsoon season (Ara et al. 2021). In addition, the recent studies, such as those conducted by Zheng et al. (2017) and Blaško et al. (2020), highlight tree species identity as a significant determinant of soil properties. These studies speculate that SOC undergoes substantial alterations in the topsoil (0-10 cm), while changes in the deeper subsoil layers (10-30 cm) are relatively minor when tree species identity varies. Although species-specific effects on soil carbon storage are more apparent in the top 20 cm soil layer (Mueller et al. 2012), our results suggest that all observed plantations may be equally effective at improving soil quality and sequestering carbon in the surface soil layer (up to 20 cm), with the effectiveness declining in *M. champaca* plantations at greater soil depths (>20 cm). The reasons behind such species-specific effects on soil properties would possibly be the variation of species traits leading to quantity and quality of litter's inputs to soil (Rai et al. 2021), the inherent variability of soil, seasonal variations, and overall environmental conditions (Ondrasek et al. 2019). However, we conducted our study at the local scale to reduce inherent variability of soils and the environment. Further study at the regional scale is recommended for understanding more detail about the seasonal, environmental, and soil variability effects on species-specific influence on soil properties.

Previous studies also showed that the species diversity positively increases soil C storage (Gamfeldt et al. 2013, Forrester et. al. 2013, Li et al. 2020). Soil carbon storage is highly positively correlated with aboveground biomass (Forrester et al. 2013), and enhanced through input by litter and fine roots (Berger et al. 2002, Dawud et al. 2016, Araújo et al. 2022). Since the litter is one of the main sources of SOC (Ondrasek et al. 2019, Rai et al. 2021), the higher C storage in soil was expected to be mediated through the higher litter accumulation. In addition, the higher C content in soil increases by higher input of organic matter with a lower decomposition rate (Moorhead & Sinsabaugh 2006), therefore, C stored in the ecosystem is the difference between net gain through primary production and loss by decomposition (Ontl et al. 2012, Ondrasek et al. 2019). In our study, species-specific effects on soil properties were investigated from two mono-species plantations; *T. grandis*, as a deciduous species that produce a higher quantity of litter through complete leaf shedding in the dry season (Prasetyawati & A'ida 2019), and a semi-evergreen *M. champaca* (Karthikeyan et al. 2016). However, we did not observe significant changes in the litter layer among the examined plantation types, which is consistent with a recent study by Rahman et al. (2022), who also recorded no variation in litter layer depth (5.2-6.5 cm) across the same studied area of KNP, elaborating 25 different tree species on 40 main plots and 80 micro-plots. Similarly, in the Jaldapara National Park, Indian Eastern Himalayan region, the authors have not observed significant differences in either annual litter production or its decomposition rates among five distinct forest stands, including *T. grandis* and *M. champaca* (Rai et al. 2021). Litter decomposition is commonly influenced by a combination of factors, including soil microbiota (Purahong et al. 2014), tree eco-physiological properties (e.g. deciduous or evergreen leaf biomass, chemical composition of litter), pedolological and climate conditions (Ondrasek et al. 2019), and various forest management practices (Rai et al. 2021). Moreover, *T. grandis* leaves are larger with a thicker cuticle that decomposes slowly as compared to *M. champaca* leaves (Karthikeyan et al. 2016, Prasetyawati & A'ida 2019). Therefore, we assumed that quality variations in the litter among examined plantations might impact its decomposition rate, ultimately influencing SOC concentration, as observed only in the deepest soil layer. Thus, the slower decomposition of *T. grandis* leaf litters may persist into deep soil as fragmented and partially decomposed materials for a longer time as compared to *M. champaca* leaf litters, which may result in higher organic carbon storage in deeper soil layers at *T. grandis* plantation site (Table 2, Figure 2).

Similarly to SOC, the total N concentration over the soil profiles among studied plantation sites was uniform, with a significant difference only in the deepest soil layer (20-30 cm), where *M. champaca* and mixed-species plantation obtained the lowest N concentration in contrast to *T. granidis* plantation (Table 2, Figure 3). The mechanism for such N deposition over the soil layers can be explained by N input from the decomposed biomass (e.g. litters), and its output through the leaching, soil erosion and/or phyto-uptake (Ondrasek et al. 2021, Ara et al. 2021). Thus, our results suggest that observed plantations may be equally effective in the decomposition of litter biomass in the surface soil layer (up to 20 cm), with the effectiveness declining in *M. champaca* and mixed-species plantations at deeper (>20 cm) soil layers. To support this, a recent study in the same area of KNP did not find a correlation between tree species distribution and soil organics, attributing such outcomes to the erosion loss of organic matter during the monsoon season (Ara et al., 2021). In addition, previous studies have indicated higher soil nutrient mineralization in the mixed-species plantation than in mono-species plantation (Richards et al. 2010), and higher N input than leaching in the topsoil layers occurs when tree diversity increases (Zheng et al. 2017). In addition, Oelmann et al. (2010) also speculated no changes in nutrient pools in the root zone between mixed and mono species tropical tree plantations. However, further investigations on species-specific effects on litter decomposition and nutrient leaching with seasonal variations are recommended to understand more detail about species-specific effects on soil N accumulation.

We found some changes in the accumulation of available P content of soils across plantation sites, but the changes were insignificant regardless of soil depth and plantation type (Table 2, Figure 4). The absence of variation in P concentration over the soil profile and among different plantation types is intriguing, given that *T. grandis* and *M. champaca* are recognized for their distinct rooting depths and nutrient uptake strategies, which potentially can result in divergent P availability. The lack of significant differences in the concentration of available P suggests that the factors that influence P availability are relatively consistent throughout the examined site and that the different plantation types do not have a major impact on P availability. Namely, it was confirmed that the mechanism related to nutrient exploitation in the mixed stand would be the nutrient uptake efficiency by plants (Richards et al. 2010). Nutrient uptake efficiency changes in species mixed plantation through the modification of fine root architecture (Wambsganss et al. 2021, Meriño-Gergichevich et al. 2021), and enhanced root symbiosis may result in greater soil nutrient capture in mixture as compared to monoculture (Wambsganss et al. 2021); thus, nutrient exploitation potentiality differs in the mixed species stand as compared to mono species stands.

The similar mechanisms of organic matter losses (discussed above), may also contribute to the footprint of available K, which significance was confirmed only in the intermediate soil layer (10-20 cm) where the mixed-species plantation recorded the lowest available K concentration (Figure 5). Further investigation into the changes of root architecture and modification of root symbiosis in species mixture is recommended for a better understanding of K (and other nutrients) exploitation efficiency in the studied area.

An obvious species-specific influence on the soil pH reaction was found in this study, *T. grandis* plantation recorded the lowest soil pH reaction, which has been increased in the *M. champaca* and mixed-species plantation (Figure 6). This observed pH variation underscores the importance of better understanding and managing soil acidity in the studied area, given that soil pH is considered as a master pedovariable in nutrients biogeochemistry and ultimately plant growth performances (Ondrasek et al. 2021). In recent study performed on the same area of KNP it was found that soil pH is the most significant ($p<0.01$) pedovariable that influence the overall tree species distribution (Ara et al. 2021). Additionally, typically acidic pedosphere in KNP is primarily attributed to the presence of pre-weathered parent materials and the pronounced leaching of basic cations (Ca^{2+}, Mg^{2+}, K^{+}) during monsoon season, contributing to the development of forest Ultisols (Akhtaruzzaman et al. 2020, Ara et al.

2021). Given that tree litter serves as the primary source of soil organic matter, and considering that litter depth remained consistent across the observed plantations (discussed above), we assume that the species-specific physiochemical properties of litter may have caused substantial variations in soil pH values among plantations. For instance, a positive correlation between species diversity and soil pH has been confirmed (Price et al. 2017, Zhao et al. 2022), whereas Guckland et al. (2009) have demonstrated an increase of soil pH with increasing species diversity. The physiochemical properties of soil may vary depending on the tree species grown on it. *T. grandis* leaves are strongly acidic and its pH content is averaged 5.38, although the best growth and productivity of Tectona grandis has been observed at pH > 5.5 (Vaides López et al. 2018). In contrast, *M. champaca* plantation has been evident to increase soil pH (Orwa et al. 2009), a trend consistent with our findings. In addition, tree litter can significantly impact soil pH reactions in the forest soil through various decomposition processes (Rai et al. 2021), releasing low-/high-molecular organic acids into the soil or liberating H^+ (Ondrasek et al. 2019). Finally, understanding the intricate influence of tree litter on soil pH implies possible future research, taking into account tree species, litter chemical composition, rate of decomposition and some other physical and/or microbiological soil properties.

Conclusion

A mono-plantation of *Michelia champaca* and *Tectona grandis*, along with their mixed-species plantation were examined for pH, SOC, N, P and K concentration over the soil profile in the Khadimnagar National Park, Bangladesh. All observed pedovariables were consistent among plantation types in the topsoil layer (0-10 cm). However, significant fluctuations were observed in the intermediate soil layer (10-20 cm), where K concentrations were the lowest in *M. champaca* (19.6 mg/kg) and mixed-species plantation (17.6 mg/kg), while in *T. grandis* were recorded the highest K (27.4 mg/kg). In the deepest layer (20-30 cm), *M. champaca* and mixed-species plantations had the lowest SOC (0.55-0.66%) and N (0.05-0.06%) concentrations. In addition, soil pH reaction raised from the topsoil (5.30) to the deepest layer (7.00), indicating the leaching of basic cations (Ca^{2+}, Mg^{2+}, K^+) due to monsoon rainfalls. However, additional research is necessary to elucidate the mechanisms behind observed plantation impacts on soil variables, considering other factors (litter chemical composition, physical and microbiological soil properties), to gain valuable inputs for sustainable management of tropical semi-evergreen forests vulnerable to soil acidity and water erosion.

Compliance with ethical standards

Conflict of interest

Authors declare there is no conflict of interest.

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