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Soil carbon stock and physico-chemical properties in important plantations of Tamil Nadu, India

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Abstract**—** *Soil organic carbon (SOC) plays an important role in soil fertility and is of paramount importance for its contributions to mitigation and adaptation to climate change. The present study was undertaken to estimate the SOC stock and soil properties in important plantations of the Southern zone in Tamil Nadu. Four different species were selected for the study viz, Eucalyptus, Casuarina, Melia and Teak. In all the plantations selected for estimation of biomass, composite soil samples were collected at three different depths; i.e., 0-15, 15- 30 and 30-45 cm. The soil samples were analysed for the carbon stock and various properties such as pH, Electrical conductivity, Organic carbon, Available N, Available P, Available K. Among Eucalyptus plantations, clonal plantation of >6 years sequestered the highest amount of soil carbon (19.8 Mg ha^{-1}) at 30 cm depth. SOC stock was maximum in Casuarina plantation of > 5 years (23.3 Mg ha^{-1}). Among the different Melia plantations, maximum SOC stock was observed in Melia plantation of 5 to7 years old (15.6 Mg ha^{-1}), and in Teak plantations, SOC stock was highest in plantations of > 15 years old (22.1 Mg ha^{-1}). The soil pH and Electrical conductivity significantly differed among the plantations and decreased with an increase in the age of plantation. Nitrogen availability was highest (303.98 kg ha^{-1}) in >5 years of Casuarina clonal plantation at 0-15 cm depth. Among the plantations the available potassium was high in surface soils (0-15 cm) of >5 years Casuarina clonal plantation (329.50 kg ha^{-1}). The data generated in the present study would provide valuable information on the scope of afforestation and reforestation projects for sustaining the livelihoods of the farming community and also will encourage them to contribute to mitigating global carbon emissions and expanding forest and tree cover.*

Keywords**— *Soil carbon stock, soil properties, plantations, climate change.***

I. INTRODUCTION

Global climatic conditions due to human activities have directed towards utilizing soils as a resource to both mitigate and adapt to climate change. The importance of soils and SOC in climate change adaptation and mitigation has been widely accepted and demonstrated in various studies (Scharlemann et al. 2014)**.** At global level, Soil Organic Carbon (SOC) stocks are estimated at an average of 1,500 ±230 Pg C in the 100 cm of soil, and this is nearly twice as that of atmospheric carbon (828 Pg C) and thrice as that of terrestrial vegetation (500 Pg C) (Quere et al. 2016). The Intergovernmental Panel on Climate Change identified creation and strengthening of carbon sinks in the soil as a clear option for increasing removal of CO_2 from the atmosphere and has recognized soil organic carbon pool as one of the five major carbon pools for the Land Use, Land Use Change in Forestry (LULUCF) sector (IPCC, 2003). As an important indicator of soil health, SOC is important for its contributions to food production, mitigation and adaptation to climate change, and the achievement of the Sustainable Development Goals (SDGs). Judicious soil management needs to be implemented to ensure that soil is rendered a sink rather than a source of atmospheric CO_2 by considering the role of soils in climate change mitigation and adaptation (Paustian *et al*., 2016). Therefore, it is ideal to study and determine, for any given ecosystem, the current SOC stocks to determine a soil's carbon sequestration potential. The role of soils and SOC in climate change adaptation and mitigation has been widely recognized and validated in various studies, both experimentally and through modelling (Scharlemann *et al*., 2014)**.** Studies on soil organic carbon stock and properties under important plantations *viz,* Eucalyptus, Casuarina, Melia and Teak in the Southern zone of Tamil Nadu, India using IPCC guidelines are lacking. Therefore, the present study aims to assess the carbon stock and soil properties in important plantations in the Southern zone of Tamil Nadu.

II. MATERIALS AND METHODS

The study was conducted in the Southern agro-climatic zone of Tamil Nadu. The Southern zone is situated between 8° and 10° 55' North latitude and 77° and 79° 50' East longitude. The Southern zone consists of Tirunelveli, Virudhunagar, Ramanathapuram, Thoothukudi, Sivagangai, Madurai (Tirumangalam, Madurai South, Madurai North and Melur taluks) and Dindigul (Natham and Dindigul taluks). The zone receives a mean annual rainfall is 876.4 mm. The maximum temperature ranges between 30.0° C and 37.5° C, while the range of minimum temperature is 20.0° C to 27.0° C. Predominant soil types occurring in this zone are black soil, red soil, deep red loam soil, red sandy soil, lateritic soil, river alluvium and saline coastal alluvium.

Soil sampling

The existing stands of three different ages of tree plantations viz, Eucalyptus, Casuarina, Melia and Teak were selected from within the available plantations on farmlands. In all the selected plantations composite soil samples were collected at three different depths; i.e., 0-15, 15- 30 and 30-45 cm. Soil samples were collected in four cardinal directions around the tree and mixed in equal proportions to form a composite sample for each layer. At each sampling point, an area of 0.5m x 0.5m was removed and a pit of 50cm wide, 50 cm in length and 45cm deep was dug. The soil was scrapped from three sides of the pit with the help of a kurpee at each depth. The soil was mixed thoroughly and transferred to a polythene bag with proper labeling. Latitude, longitude and altitude of each sampling point were recorded by GPS.

Soil preparation

The collected soil samples were air dried in shade and powdered to fine soil particles using wooden mallet. The soil thus prepared was sieved through 2.0 mm sieve and stored in cloth bags. A small portion of each sample was again sieved through 0.2 mm sieve for analysis of organic carbon.

Soil carbon stock estimation

Soil organic carbon was estimated by standard Chromic acid wet oxidation method of Walkley and Black (1934). Organic matter in the soil was oxidized with the mixture of potassium dichromate and concentrated sulphuric acid, utilizing the heat of dilution of sulphuric acid. Unused potassium dichromate was back titrated with ferrous ammonium sulphate. Two to three clods of 2mm size were collected from each pit for estimating bulk density. Bulk density was estimated by the wax coating (clod) method. The clods were wrapped in cotton and placed in plastic containers to avoid breakage during transportation of the clods to the laboratory. In the laboratory, the clods were tied with a thread and dipped in molten wax to coat the clod surface. The wax coated clod was dipped in water and the bulk density was determined from the volume of water displaced. The per cent of coarse fragments was quantified by visual observation of the area occupied by coarse fragments. Soil organic carbon pool was estimated up to the depth of 45 cm in this study. Soil organic carbon pool was calculated by using the following equation as suggested by IPCC Good Practice Guidelines for LULUCF (2003).

$$\text{SOC} = \sum_{\text{Horizon}=1}^{\text{Horizon}=n} \text{SOC}_{\text{horizon}} = \sum_{\text{Horizon}=1}^{\text{Horizon}=n} \left([\text{SOC}] * \text{Bulk density} * \text{Depth} * (1-\text{C frag}) * 100\right)_{\text{horizon}}$$

Where,

SOC = Representative soil organic carbon content for the forest type and soil of interest, tonnes C ha^{-1}.

$\text{SOC}_{\text{Horizon}}$ = Soil organic carbon content for a constituent soil horizon, tonnes C ha^{-1}

[SOC] = Concentration of SOC in a given soil mass obtained from analysis, g C (kg soil)$^{-1}$

Bulk density = Soil mass per sample volume, tonnes soil m^{-3}(equivalent to Mg m^{-3})

Depth = Horizon depth or thickness of soil layer, m

C frag = % volume of coarse fragments/100, dimensionless.

Estimation of soil properties

The soil samples were analysed for the various properties such as pH, Electrical conductivity, Available N, Available P, Available K. The detailed methods are described below. The pH of soil was determined using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using a pH meter (Jackson, 1973). The electrical conductivity of soil was determined using an aqueous suspension of soil (soil and water in 1:2.5 ratio) using a conductivity meter (Jackson, 1973). The available nitrogen in the soil was estimated by the alkaline permanganate method. The amount of soil nitrogen released due to the oxidation of part of soil organic matter by $KMnO_4$ was estimated by distillation with NaOH (Subbiah and Asija, 1956). Available phosphorus was determined by the Olsen method. Blue colour was developed using ascorbic acid and the intensity of colour was measured using a spectrophotometer at 660 nm (Olsen *et al.*, 1954). In the Bray method, available P was commonly extracted using Bray No. 1 which consisted of 0.03 NH_4F and 0.025 HCl. The extracted phosphorus was measured colorimetrically based on the reaction with ammonium molybdate and development of the ‘Molybdenum Blue’ colour. The absorbance of the compound was measured at 882 nm in a spectrophotometer and is directly proportional to the amount of phosphorus extracted from the soil and Bray and Kurtz, 1945). Exchangeable potassium in the soil samples were extracted using 1N ammonium acetate and estimated using flame photometer (Stanford and English, 1949).

All statistical tests were performed with SPSS ® 19.0 version statistical software. One-way analysis of variance (ANOVA) was used to assess the biomass carbon and soil carbon sequestration. Duncan’s test was performed to separate means if differences were significant (P=0.05).

III. RESULTS AND DISCUSSION

Soil represents the major reservoir of terrestrial carbon pool and the amount of carbon stored in soil organic matter is one of the largest and most dynamic reservoirs of carbon in the global carbon cycle. The organic carbon content in plantations of the Southern zone ranged from 0.29 ± 0.00 to 0.68 ± 0.00 (Table 1) and was found between low to medium in range. The lowest soil OC (0.29 %) was recorded under >7 years of Melia at 30-45cm. The maximum OC (0.68 %) was recorded in Casuarina clonal plantation of > 5 years at 0-15 cm depth, followed by >5 years of Casuarina plantation of seedling origin (0.67%), >6 years of Eucalyptus clonal plantation (0.62), >15 years of Teak (0.60 %), >6 years of Eucalyptus plantation of seedling origin, (0.58%) and > 7 years of Melia (0.52%) at 0-15 cm plantations. Among the plantations, the maximum OC was recorded in older plantations. The trend of changing SOC content in the different plantations along the age was significantly different ($p \leq 0.05$) and increased with an increase in the age of the plantation. However, SOC decreased with an increase in soil depth. The increase in SOC content at the surface soil layer is attributed to higher amount of carbon input from litterfall, dead roots, and root exudates (Chauhan et al., 2010 and Kaushal et al., 2012).

The bulk density of plantations of the Southern zone ranged from 1.25 ± 0.02 to 1.40 ± 0.01 (Table 1). The minimum soil bulk density (1.25 g/cc) was observed under 0-15 cm of >5 years of Casuarina clonal plantation. The highest bulk density (1.40 g/cc) was observed in 2 to 4 years of Melia at 30-45 cm followed by 1 to 2 years of seedling origin Casuarina plantation (1.40 g/cc) followed by Casuarina clonal plantation of 1 to 2 years of (1.39 g/cc), 5 to 10 years of Teak (1.39 g/cc), 1 to 2 years of Eucalyptus clonal plantation (1.37 g/cc) and 4 to 5 years of Eucalyptus plantation of seedling origin (1.36 g/cc) plantations at 30-45 cm depth. The measured bulk density was significantly varied ($P \leq 0.05$) and decreased with the increasing age of plantations. However, in 4 to 5 years of seedling origin Eucalyptus plantation, the bulk density increased at 30-45 cm. Among the different depths, the BD was low in surface (0-15 cm) compared to lower depths and increased with depth increment for all the plantations. The increase in bulk density is largely due to decreasing organic matter content and reduced aggregation with depth (Chauhan et al. 2018).

Soil organic carbon stock of different plantations is given in Tables 2 and Fig.1. In Eucalyptus plantation, clonal plantation of >6 years sequestered the highest amount of soil carbon (19.8 Mg ha^{-1}) at 30 cm depth, SOC stock was maximum in Casuarina plantation of > 5 years (23.3 Mg ha^{-1}), among the different Melia plantations, maximum SOC stock was observed in Melia plantation of 5 to7 years old (15.6 Mg ha^{-1}), and in Teak plantations, SOC stock was highest in plantations of > 15 years old (22.1 Mg ha^{-1}). The increase in SOC content at the surface soil layer is attributed to higher amount of carbon input from litterfall, dead roots, and root exudates (Chauhan et al., 2010 and Kaushal et al., 2012). Gupta et al. (2009) also reported that SOC increased significantly with age of plantation in the 0–15 cm soil layer and was 18% higher under 3-year plantations than in the soils under 1-year plantations.

Table 1. Soil organic carbon (%) and soil properties in the Southern zone

Plantation type	Soil Depth	pH	EC (dS m^{-1})	OC (%)	BD (g/cc)	pH	EC (dS m^{-1})	OC (%)	BD (g/cc)	pH	EC (dS m^{-1})	OC (%)	BD (g/cc)
Eucalyptus		**1 to 2 Years**				**4 to 5 Years**				**>6 Years**			
	0-15	6.28±0.24^{abc}	0.08±0.00	0.40±0.00^{c}	1.29±0.01^{ab}	6.08±0.07^{ab}	0.08±0.00	0.52±0.00^{g}	1.27±0.01^{a}	5.99±0.05^{a}	0.07±0.00	0.58±0.00^{h}	1.26±0.00^{a}
	15-30	6.35±0.05^{bc}	0.08±0.00	0.36±0.00^{b}	1.32±0.01^{bc}	6.14±0.06^{ab}	0.06±0.00	0.48±0.00^{f}	1.31±0.02^{bc}	6.12±0.05^{ab}	0.06±0.00	0.44±0.00^{e}	1.28±0.01^{ab}
	30-45	6.58±0.05^{c}	0.11±0.00	0.34±0.00^{a}	1.34±0.01^{cd}	6.18±0.05^{ab}	0.05±0.00	0.42±0.00^{d}	1.36±0.00^{d}	6.36±0.05^{bc}	0.04±0.00	0.41±0.00^{cd}	1.31±0.00^{bc}
Eucalyptus Clone		**1 to 2 Years**				**4 to 5 Years**				**>6 Years**			
	0-15	6.30±0.05^{ab}	0.08±0.00	0.49±0.00^{c}	1.30±0.01^{abc}	6.10±0.05^{ab}	0.08±0.00	0.59±0.00^{e}	1.29±0.02^{ab}	6.00±0.05^{a}	0.11±0.00	0.62±0.00^{f}	1.26±0.01^{a}
	15-30	6.65±0.24^{cd}	0.10±0.00	0.44±0.00^{b}	1.32±0.02^{bc}	6.22±0.05^{ab}	0.06±0.00	0.51±0.00^{cd}	1.31±0.01^{abc}	6.16±0.05^{ab}	0.08±0.00	0.53±0.00^{d}	1.28±0.01^{ab}
	30-45	6.78±0.09^{b}	0.13±0.00	0.39±0.00^{a}	1.37±0.01^{d}	6.38±0.07^{bc}	0.05±0.00	0.45±0.00^{b}	1.35±0.01^{cd}	6.27±0.07^{ab}	0.06±0.00	0.49±0.01^{c}	1.30±0.01^{abc}
Casuarina		**1 to 2 Years**				**3 to 5 Years**				**>5 Years**			
	0-15	6.29±0.05^{b}	0.15±0.00	0.54±0.00^{d}	1.36±0.00^{bcd}	6.28±0.09^{b}	0.18±0.00	0.62±0.00^{g}	1.34±0.01^{abc}	5.96±0.23^{a}	0.16±0.00	0.68±0.00^{g}	1.31±0.01^{a}
	15-30	6.56±0.05^{b}	0.17±0.00	0.48±0.00^{c}	1.38±0.01^{cd}	6.35±0.05^{b}	0.20±0.00	0.56±0.00^{e}	1.37±0.01^{bcd}	6.28±0.05^{b}	0.12±0.00	0.59±0.00^{f}	1.33±0.01^{ab}
	30-45	6.58±0.05^{b}	0.20±0.00	0.38±0.00^{a}	1.40±0.01^{d}	6.46±0.05^{b}	0.14±0.00	0.44±0.00^{b}	1.39±0.01^{d}	6.45±0.05^{b}	0.09±0.00	0.49±0.00^{c}	1.35±0.00^{bcd}
Casuarina Clone		**1 to 2 Years**				**3 to 5 Years**				**>5 Years**			
	0-15	7.16±0.06^{ab}	0.11±0.00	0.55±0.00^{b}	1.30±0.01^{abc}	7.00±0.06^{a}	0.11±0.00	0.60±0.00^{e}	1.28±0.03^{ab}	6.98±0.06^{a}	0.08±0.00	0.68±0.00^{f}	1.25±0.02^{a}
	15-30	7.21±0.08^{ab}	0.14±0.00	0.48±0.00^{b}	1.35±0.04^{cd}	7.13±0.08^{ab}	0.09±0.00	0.52±0.00^{c}	1.33±0.02^{bcd}	7.06±0.10^{a}	0.06±0.00	0.57±0.00^{d}	1.27±0.02^{ab}
	30-45	7.36±0.08^{b}	0.17±0.00	0.40±0.00^{a}	1.39±0.01^{d}	7.24±0.08^{ab}	0.07±0.00	0.42±0.00^{a}	1.35±0.02^{cd}	7.17±0.10^{ab}	0.04±0.00	0.50±0.01^{c}	1.30±0.02^{abc}
Melia		**2 to 4 Years**				**5 to 7 Years**				**>7 Years**			
	0-15	6.98±0.08^{ab}	0.17±0.00	0.46±0.00^{f}	1.30±0.01^{abc}	6.95±0.08^{ab}	0.16±0.00	0.50±0.00^{a}	1.26±0.01^{ab}	6.86±0.06^{a}	0.08±0.00	0.52±0.00^{h}	1.26±0.02^{a}
	15-30	7.16±0.06^{ab}	0.19±0.00	0.38±0.00^{c}	1.37±0.00^{de}	6.99±0.06^{ab}	0.13±0.00	0.40±0.00^{d}	1.31±0.01^{bc}	6.90±0.08^{a}	0.06±0.00	0.42±0.00^{e}	1.29±0.00^{abc}
	30-45	7.23±0.16^{b}	0.21±0.00	0.30±0.00^{ab}	1.40±0.01^{e}	7.11±0.10^{ab}	0.12±0.00	0.31±0.00^{b}	1.33±0.01^{cd}	7.11±0.03^{ab}	0.05±0.00	0.29±0.00^{a}	1.33±0.02^{cd}
Teak		**5 to 10 Years**				**11 to 15 Years**				**>15 Years**			
	0-15	5.74±0.06^{a}	0.17±0.00	0.48±0.00^{d}	1.33±0.01^{abcd}	5.62±0.08^{a}	0.14±0.00	0.55±0.00^{e}	1.31±0.01^{ab}	5.62±0.05b^{c}	0.07±0.00	0.60±0.00^{f}	1.29±0.01^{a}
	15-30	6.16±0.22^{b}	0.19±0.00	0.38±0.00^{c}	1.39±0.05^{cd}	5.78±0.05^{a}	0.12±0.00	0.46±0.00^{d}	1.33±0.00^{abcd}	5.78±0.05^{cd}	0.06±0.00	0.55±0.01^{e}	1.32±0.00^{abc}
	30-45	6.21±0.07^{b}	0.23±0.00	0.30±0.00^{a}	1.39±0.01^{d}	6.08±0.05^{b}	0.09±0.00	0.34±0.00^{b}	1.36±0.01^{bcd}	6.08±0.06^{d}	0.04±0.00	0.46±0.00^{d}	1.35±0.00^{abcd}

Mean values with lower case superscript letters indicate significant difference between different aged plantations across different depths at (P ≤ 0.05). ± indicates standard error

Table 2: SOC stock in (Mg C ha^{-1}) plantations of the Southern zone

Plantation type	**Soil Depth**	**SOC stock (Mg ha^{-1})**		
		1 to 2 Years	**4 to 5 Years**	**>6 Years**
Eucalyptus	0-15	7.4±0.06^{a}	9.7±0.11^{c}	10.6±0..09^{d}
	15-30	13.3±0.0.11^{f}	18.1±0.20 ^{h}	16.1±0.14^{g}
	30-45	17.8±0.16^{h}	21.7±0.24^{l}	20.7±0.18^{k}
		1 to 2 Years	**4 to 5 Years**	**>6 Years**
Eucalyptus Clone	0-15	8.9±0.07^{b}	11.1±0.12^{e}	11.5±0.10^{e}
	15-30	16.2±0.14^{g}	18.9±0.21^{i}	19.9±0.17^{j}
	30-45	19.5±0.17^{j}	23.2±0.26^{m}	25.9±0.22^{n}
		1 to 2 Years	**3 to 5 Years**	**>5 Years**
Casuarina	0-15	8.7±0.07^{a}	11.3±0.09^{c}	12.4±0.10^{d}
	15-30	18.5±0.16 ^{f}	22.0±0.19^{h}	23.4±0.21^{i}
	30-45	19.8±0.17^{g}	23.6±0.21^{i}	26.4±0.23^{j}
		1 to 2 Years	**3 to 5 Years**	**>5 Years**
Casuarina Clone	0-15	9.9±0.08^{b}	11.2±0.13^{c}	12.5±0.11^{d}
	15-30	17.5±0.15^{e}	19.9±0.22^{g}	22.1±0.19^{h}
	30-45	20.0±0.17^{g}	21.8±0.25^{h}	26.8±0.23^{j}
		2 to 4 Years	**5 to 7 Years**	**>7 Years**
Melia	0-15	8.3±0.07^{a}	9.4±0.08^{b}	9.4±0.08^{b}
	15-30	14.3±0.12^{c}	15.7±0.13^{f}	15.6±0.13^{ef}
	30-45	15.3±0.13^{e}	16.6±0.15^{g}	14.8±0.13^{d}
		5 to 10 Years	**11 to 15 Years**	**>15 Years**
Teak	0-15	9.0±0.07^{a}	10.5±0.38^{b}	11.5±0.42^{b}
	15-30	14.5±0.12 ^{c}	17.4±0.64 ^{d}	21.5±0.79 ^{e}
	30-45	15.6±0.14^{c}	17.8±0.66^{d}	24.5±0.91^{f}

Mean values with lower case superscript letters indicate significant difference between different aged plantations across different depths at (P ≤ 0.05). ± indicates standard error

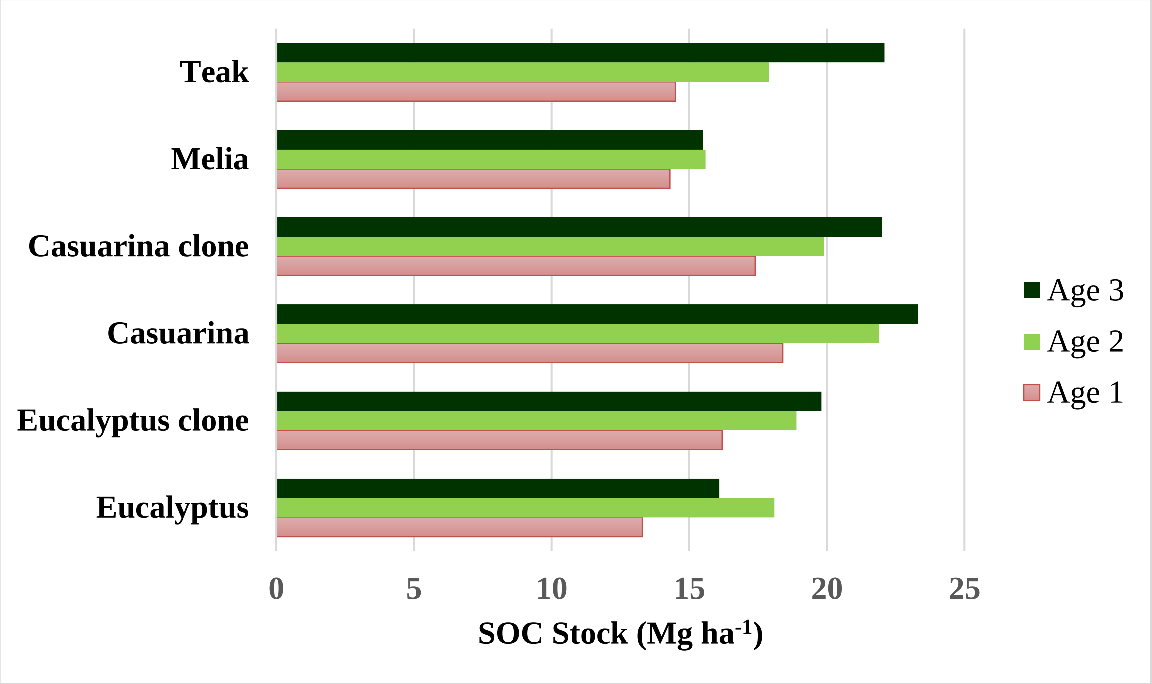

Fig. 1. Soil Organic Carbon stock (Mg ha^{-1}) of different plantations in the Southern zone

The mean soil reaction (pH) in plantations of the Southern zone is given in Table 21. The overall soil pH varied from 5.62 ± 0.05 to 7.36 ± 0.08 and the samples were slightly acidic to neutral in range. Among the different plantations the minimum soil pH of 5.62 was recorded in >15 years of Teak plantation at 0-15 cm depth and the maximum of 7.36 was recorded in 1 to 2 years of Casuarina clonal plantation at 30-45 cm depth. The soil pH was significantly different and decreased with an increase in the age of plantation except >6 years of Eucalyptus plantation of seedling origin at 30-45 cm depth, where it was slightly increased. The surface soils (0-15 cm) of older aged Eucalyptus seedling origin plantation, Eucalyptus clonal plantation, Casuarina seedling origin plantation, and Teak plantations revealed that the pH was acidic in range while in Melia and Casuarina clonal plantation the pH was neutral. However, the soil pH increased with depth increment. The increased pH at lower soil depth might be due to leaching and accumulation of basic cations in deep soil profiles (Kumar et al. 2018).

The mean soil electrical conductivity in plantations of the Southern zone ranged from 0.04 ± 0.00 to 0.23 ± 0.00 (Table 1) and was non-saline. Among the plantations the minimum soil EC (0.04 dS m^{-1}) was observed under >15 years of Teak plantation at 0-15 cm depth and the highest EC (0.23 dS m^{-1}) was observed in 5 to 10 years of Teak plantation at 30-45 cm depth. The electrical conductivity (EC) significantly ($P \leq 0.05$) decreased with the increasing age of the plantation and increased with depth increment.

The available nitrogen content in plantations of the Southern zone ranged between 165.84 ± 1.47 to 303.98 ± 2.69 (Table 3) and was found between the low to medium range. The lowest available nitrogen 165.84 kg ha^{-1} was recorded under 1 to 2 years of seedling origin Eucalyptus plantation at 30-45 cm depth and the maximum available nitrogen 303.98 kg ha^{-1} was recorded in >5 years of Casuarina clonal plantation at 0-15 cm depth. Among the plantations, the available nitrogen was medium in the surface layer (0-15 cm) of > 5 years Casuarina clonal plantation (303.98 kg ha^{-1}), >5 years of Casuarina plantation of seedling origin (299.40 kg ha^{-1}), and > 15 years of Teak (298.10 kg ha^{-1}), while it was low in Eucalyptus plantation of seedling origin, Eucalyptus clonal plantation and Melia plantations. The available phosphorus content in plantations of the Southern zone ranged from 13.95 ± 0.35 to 24.62 ± 0.22 (Table 3) and was found between medium to high in range. The minimum available phosphorus of 13.95 kg ha^{-1} was recorded under >7 years of Melia at 30-45 cm depth and the maximum 24.62 kg ha^{-1} was recorded in >5 years of seedling origin Casuarina plantation at 0-15 cm depth. The maximum available phosphorus content was recorded in the surface soils (0-15 cm) of >5 years of seedling origin Casuarina plantation (24.62 kg ha^{-1}) followed by >5 years of Casuarina clonal plantation (23.82 kg ha^{-1}), >6 years of Eucalyptus plantation of seedling origin (23.52 kg ha^{-1}) and >6 years of Eucalyptus clonal plantation (22.73 kg ha^{-1}) while, it was medium in >7 years of Melia (21.70 kg ha^{-1}) and >15 years of Teak (20.66 kg ha^{-1}) plantation. However, the available phosphorus concentration found in the soil under different plantation forests significantly varied ($p \leq 0.05$) and it increased with an increase in the age of plantation except for >7 years of Melia plantation, where it decreased at 30-45 cm depth. However, the phosphorus concentration decreased with an increase in soil depth. Higher availability of nutrients on surface layers under different plantations might be due to accumulation and decomposition of litterfall on the soil surface as well as its incorporation in the soil surface layers. It assists in the mineralization of organic N and P from the litter and its release into the soil (Singh and Sharma, 2007).

Table 3. Available macronutrients status in different plantations of the Southern zone

Plantation type	**Soil Depth**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**	**N (kg ha^{-1})**	**P (kg ha^{-1})**	**K (kg ha^{-1})**
Eucalyptus		**1 to 2 Years**			**4 to 5 Years**			**>6 Years**		
	0-15	197.94±1.75^{d}	19.14±0.17^{f}	249.56±2.21^{f}	219.66±1.94^{f}	21.33±0.19^{ij}	265.91±2.35^{h}	233.82±2.07^{h}	23.52±0.21^{l}	289.43±2.56^{j}
	15-30	173.17±1.52^{b}	16.46±0.14^{cd}	226.35±1.99^{cd}	200.60±2.32^{d}	19.20±0.22^{f}	230.70±2.66^{d}	213.89±1.89^{f}	20.43±0.18^{gh}	270.00±2.39^{hi}
	30-45	165.84±1.47^{a}	14.25±0.13^{a}	199.63±1.77^{a}	180.00±1.59^{c}	16.34±0.14^{c}	215.68±1.91^{b}	197.74±1.75^{d}	17.84±0.16^{e}	245.98±2.18^{ef}
Eucalyptus Clone		**1 to 2 Years**			**4 to 5 Years**			**>6 Years**		
	0-15	207.31±1.83^{e}	19.97±0.24^{g}	251.16±2.22^{fg}	223.85±1.98^{g}	21.60±0.25^{j}	269.40±2.38^{hi}	247.57±2.19^{i}	22.73±0.33^{k}	290.45±3.51^{j}
	15-30	184.16±2.23^{c}	16.89±0.20^{cd}	229.73±2.03^{d}	201.80±2.33^{de}	19.30±0.23^{f}	241.59±2.14^{e}	220.07±3.21^{f}	20.83±0.31^{hi}	275.38±2.44^{i}
	30-45	169.06±2.05^{ab}	14.95±0.13^{b}	204.02±1.80^{a}	182.60±2.11^{c}	17.04±0.15^{d}	219.87±1.95^{bc}	197.74±2.88^{d}	18.14±0.16^{e}	257.54±2.28^{g}
Casuarina		**1 to 2 Years**			**3 to 5 Years**			**>5 Years**		
	0-15	289.43±2.56^{e}	21.33±0.19^{gh}	299.70±2.65^{d}	295.81±2.62^{ef}	23.72±0.21^{k}	316.94±2.80^{e}	299.40±2.65^{fg}	24.62±0.22^{l}	329.50±2.92^{f}
	15-30	273.69±2.42^{cd}	18.54±0.16^{bc}	274.68±2.43^{bc}	267.81±2.37^{c}	20.33±0.18^{f}	296.11±2.62^{d}	279.46±2.47^{d}	21.63±0.19^{ghi}	318.64±2.82^{e}
	30-45	249.37±2.20^{b}	16.34±0.14^{a}	249.87±2.21^{a}	239.80±2.12^{a}	18.14±0.16^{b}	275.48±2.44^{bc}	254.05±2.25^{b}	19.64±0.17^{de}	297.40±2.63^{d}
Casuarina Clone		**1 to 2 Years**			**3 to 5 Years**			**>5 Years**		
	0-15	292.02±2.58^{ef}	22.05±0.27^{i}	299.70±2.65^{d}	298.00±2.64^{fg}	22.80±0.27^{j}	316.94±2.80^{e}	303.98±2.69^{g}	23.82±0.35^{k}	329.50±2.92^{f}
	15-30	273.69±2.42^{cd}	18.87±0.23^{c}	277.07±2.45^{bc}	267.81±2.37^{c}	21.00±0.24^{g}	295.41±2.61^{d}	289.03±2.56^{e}	21.73±0.32^{hi}	300.20±2.65^{d}
	30-45	252.84±2.22^{b}	16.65±0.15^{a}	254.15±2.25^{a}	254.70±2.94^{b}	19.04±0.17^{cd}	269.10±2.38^{b}	274.48±2.43^{cd}	19.87±0.24^{ef}	278.53±3.37^{c}
Melia		**2 to 4 Years**			**5 to 7 Years**			**>7 Years**		
	0-15	209.00±4.38	20.26±0.42^{e}	199.46±4.18^{c}	226.80±4.54^{e}	21.70±0.43^{f}	220.90±2.55^{d}	270.50±6.83^{g}	20.63±0.52^{e}	246.98±3.60^{e}
	15-30	199.73±3.06^{c}	16.34±0.25^{b}	194.75±1.72^{c}	197.94±3.03^{c}	19.33±0.30^{d}	184.09±1.63^{b}	249.56±3.82^{f}	15.75±0.24^{b}	220.06±1.95^{d}
	30-45	185.16±3.88^{b}	14.10±0.30^{a}	173.44±2.10^{a}	172.40±3.45^{a}	17.30±0.35^{c}	166.40±1.92^{a}	224.65±5.67^{e}	13.95±0.35^{a}	198.04±2.89^{c}
Teak		**5 to 10 Years**			**11 to 15 Years**			**>15 Years**		

	0-15	285.34±4.37^{e}	17.54±0.27^{d}	269.90±4.14^{c}	289.43±4.44^{e}	19.23±0.30^{e}	287.44±4.40^{d}	298.10±6.25^{e}	20.26±0.42^{f}	298.10±6.25^{d}
	15-30	263.32±4.03^{cd}	15.15±0.23^{a}	249.77±3.83^{b}	269.60±4.13^{d}	16.94±0.26^{cd}	253.75±3.89^{b}	286.85±17.96^{e}	18.79±1.18^{e}	271.86±17.03^{c}
	30-45	239.50±3.67^{a}	14.95±0.23^{a}	225.64±3.46^{a}	249.87±3.83^{ab}	15.65±0.24^{ab}	234.02±3.59^{a}	252.90±5.30^{bc}	16.19±0.34^{bc}	268.80±5.64^{c}

Mean values with lower case superscript letters indicate significant difference between different aged plantations across different depths at ($P \leq 0.05$). ± indicates standard error

The available potassium content in plantations of the Southern zone ranged from 166.40 ± 1.92 to 329.50 ± 2.92 and was found between medium to high in range. The minimum available potassium 166.40 kg ha^{-1} was recorded under 5 to 7 years of Melia plantation at 30-45 cm and the maximum 329.50 kg ha^{-1} was recorded in >5 years of Casuarina clonal plantation at 0-15 cm depth (Table 3). Among the plantations the available potassium was high in surface soils (0-15 cm) of >5 years Casuarina clonal plantation (329.50 kg ha^{-1}), >5 years of seedling origin Casuarina plantation (329.45 kg ha^{-1}), >15 years of Teak (298.10 kg ha^{-1}), >6 years of seedling origin Eucalyptus (290.45 kg ha^{-1}) and >6 years of Eucalyptus clonal plantation (289.43 kg ha^{-1}), while it was medium in Melia (246.98 kg ha^{-1}) plantation. The available potassium in the different plantations significantly varied ($p \leq 0.05$) and it increased with an increase in the age of the plantation except for 5 to 7 years of Melia plantation at 15-30 and 30-45 cm, where it was slightly reduced in all depths. However, with increase in the soil depth, the potassium content decreased. Chauhan et al. (2018) also reported higher availability of soil nitrogen, phosphorus and potassium (kg ha^{-1}) under different plantations at various soil depths. Nutrient availability was higher in the top 0-15 cm of the soil profile which might be due to the surface layer enrichment through nutrient cycling and decreased with the increased soil depth,

IV. CONCLUSION

Soil organic carbon is an indicator of both soil quality and environmental stability. The study has generated baseline data on soil organic carbon stock and soil properties in important plantations of the Southern zone of Tamil Nadu, India. The present study identified suitable plantation species of clonal and seedling origin for enhanced storage of soil organic carbon. The data generated in the present study would provide valuable information on the scope of afforestation and reforestation projects for sustaining the livelihoods of the farming community and also will encourage them to contribute to mitigating global carbon emissions and expanding forest and tree cover.

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