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RESEARCH ARTICLE

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Oil palm cultivation enhances soil pH, electrical conductivity, concentrations of exchangeable calcium, magnesium, and available sulfur and soil organic carbon content

Sanjib K. Behera[1,2] | **Arvind K. Shukla**[2] | **Kancherla Suresh**[1] | **Kamireddy Manorama**[1] | **Ravi K. Mathur**[1] | **Anil Kumar**[3] | **Parasa Harinarayana**[1] | **Chandra Prakash**[2] | **Ajay Tripathi**[2]

[1]Soil and Leaf Analysis Laboratory, ICAR-Indian Institute of Oil Palm Research, Eluru, Andhra Pradesh, India

[2]AICRP Micronutrient, ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India

[3]Division of Design of Experiments, ICAR-Indian Agricultural Statistics Reserach Institute, New Delhi, India

Correspondence
Arvind K. Shukla, AICRP Micronutrient, ICAR-Indian Institute of Soil Science, Nabibagh, Berasia Road, Bhopal, Madhya Pradesh 462 038, India.
Email: arvindshukla2k3@yahoo.co.in

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Abstract

The land area under oil palm (*Elaeis guineensis* Jacq.) cultivation (OPC) is increasing in different parts of world. Assessment of the soil parameters of oil palm plantations (OPP) is essential to judge the sustainability of land use for maintaining soil fertility and avoiding land degradation. The effects of OPC in India on soil parameters are poorly understood. Therefore, we evaluated the impact of OPC over the years (by considering oil palm plantations of 6, 12, and 18 years age) on soil properties, nutrient availability, soil organic carbon (SOC) pools, and SOC stock in comparison with those parameters in adjacent fallow land (FL) of southern India. Soils of OPP showed enhanced soil pH value, electrical conductivity, the concentrations of exchangeable calcium and magnesium and available sulfur, and SOC content in 0–20, 20–40, and 40–60 cm depths of soil compared with those parameters in FL. Available phosphorus concentration in soil increased with plantation age revealing the need for rational phosphorus management. However, the concentration of available nitrogen, potassium, exchangeable calcium and magnesium, and available sulfur and boron did not change with plantation age. The contents of SOC and very labile carbon were higher in surface soil layers of OPP than that in FL. Oil palm cultivation led to 20, 18, and 45% enhancement in SOC stock in 6, 12, and 18 years-old OPP, respectively, compared with SOC stock in FL indicating C sequestration due to OPC. The very labile and less labile C stock in FL, 6 and 12 years-old OPP were similar, whereas the values of these parameters were higher in 18 years-old OPP. Positive correlation (p < .01) of SOC with very labile, labile, and less labile carbon pools indicated their inter-relatedness. This information will be utilized in devising rational nutrient management options for the existing as well as ensuing OPP due to variations in soil properties and available nutrients.

KEYWORDS

oil palm, plantation crop, soil organic carbon, soil properties

1 | INTRODUCTION

Sustainable land management (SLM) aims at land use for production while maintaining its production potential and environmental functions. Soil is the pivotal component of SLM (Herrick, 2000; Keesstra et al., 2018; Lal, Horn, & Kosaki, 2018). The different land uses with varied management practices influence soil properties (Dignam et al., 2018; Gong, Ran, He, & Tiyip, 2015; Niu et al., 2015; Santiago, Magdalena, Tom, & Angel, 2017). Evaluation of soil properties is an important aspect of SLM to maintain soil fertility status and dodge soil degradation processes (Lal, 2015; Zhao, Mu, Wen, Wang, & Gao, 2013). The soil properties data from long-term studies are very important for assessing the sustainability of a particular land use, which are lacking for many crops including plantation crops like oil palm grown in various regions of the world (Aga, Chane, & Melesse, 2018; Hartemink, 1998; Smith, Townsend, Choy, Hardy, & Sjogersten, 2012).

Oil palm (*Elaeis guineensis* Jacq.) is cultivated in various countries across the globe occupying an area of 14.2 million ha (Palmoilresearch, 2014). The area under oil palm cultivation (OPC) has increased in the last several years (Pirker, Mosnier, Kraxner, Havlik, & Obersteiner, 2016). In India, the area under OPC has expanded from 3,705 ha in 1984 to 0.32 million ha in 2018–2019 and is spread across 15 states (DACFW, 2019). The Country has 1.93 million ha (covering 19 states) having potential for OPC (Rethinam, Arulraj, & Rao, 2012). In India the crop is being cultivated in the fallow land and as replacement of some annual cropping [such as rice (*Oryza sativa*), maize (*Zea mays*), Tobacco (*Nicotiana tobaccum*) and vegetables] and perennial crops [such as mango (*Mangifera indica*), and coconut (*Cocos nucifera*)] as farmers get additional income by growing it.

The nutrient requirement of oil palm is high (Woittiez, van Wijk, Slingerland, van Noordwijk, & Giller, 2017). On an average, oil palm plantations in India produce 15–20 t fresh fruit bunch (FFB) ha^{-1} yr^{-1} (Prasad, Sarkar, & Jameema, 2010). The crop needs 324 kg of nitrogen (N), 60 kg of phosphorus (P), 434 kg of potassium (K), 76 kg of magnesium (Mg), and 72 kg of calcium (Ca) for production 20 t FFB ha^{-1} yr^{-1} (Mengel & Kirkby, 1987). Imbalanced use of nutrients results in occurrence of nutrient disorders especially N–K concentration imbalance, and deficiencies of boron (B), Mg, and K affecting FFB production in oil palm plantations (OPP) in India (Kalidas et al., 2017; Rao, Suresh, Behera, Ramachandrudu, & Manorama, 2014). Hence, there is need for regular monitoring of soil parameters for balanced application of nutrients based on soil nutrient status (Behera et al., 2016; Behera, Mathur, Shukla, Suresh, & Prakash, 2018; Guillaume, Holtkamp, Damris, Brummer, & Kuzyakov, 2016; Rahman et al., 2018).

Moreover, continuous mono-cropping of plantation crops with application of fertilizers affect soil fertility parameters influencing crop productivity (Ding & Cheng, 1995; Tian et al., 2011). Plantation crops influence soil properties, organic matter status, supply and availability of nutrients, and promote nutrient cycling in soil–plant systems (Arévalo-Gardini et al., 2015; Buresh & Tian, 1997; Jose, 2009; Nair, Nair, Kumar, & Haile, 2009). These crops affect nutrient supply and availability by retrieving nutrients from below the rooting zones of crops, reducing nutrient losses from leaching and erosion and enhancing nutrients release from soil organic matter. Crops take up nutrients from different soil layers and utilize them for metabolic activities. The nutrients are returned to soil after decomposition of fallen litter, added crop residue, and dead root tissues (Nair, Buresh, Mugendi, & Latt, 1999). It has also been observed that continuous fertilizer application influences soil pH and available NPK concentration and the status of soil organic carbon (SOC) content of an apple plantation of North China Plain (Ge, Zhu, & Jiang, 2018). Further, maintaining fallow land (FL) near to cultivated land is a vital agricultural management technique and it is common in oil palm growing areas of India. Fallowing facilitates easier agricultural operations in the cultivated land besides influencing soil properties and restoring soil fertility (Aguilera, Motavalli, Valdivia, & Gonzales, 2013; Doran, Elliott, & Paustian, 1998). The OPP and FL receive different management practices, which influence soil properties (Salmiyati, Idayu, & Supriyanto, 2014; Yemadje et al., 2012). The management practices like addition of recommended doses of nutrients, irrigation, crop residue addition, and weeding are carried out in OPP for improved FFB production. While, FL does not receive any input. The knowledge pertaining to soil properties and available nutrients in OPP receiving continuous fertilizer application and that in FL adjacent to OPP is limited.

Soil organic carbon supports various important ecosystem services needed for realization of sustainable development goals (Lorenz, Lal, & Ehlers, 2019). The world-wide SOC stock is higher than that in atmosphere and vegetation (Lal, 2016; Scharlemann, Tanner, Hiederer, & Kapos, 2014). The measurement, management, and maintenance of SOC are important in order to assess soil/land degradation or aggradation and to obtain soil, water, energy, and food security (Stockmann et al., 2015). Soil acts as both source and sink of carbon - based on its management, addition of biomass, and bio-climatic changes (Zomer, Bossio, Sommer, & Verchot, 2017). Growing of plantation crops like oil palm, rubber, and tea help in enhancing carbon sink potential and SOC stock of soil with increasing age of these crops (Abbas et al., 2017; Brahma, Sileshi, Nath, & Das, 2017; Nath, Brahma, Sileshi, & Das, 2018; Pulhin, Lasco, & Urquiola, 2014). They reduce emission of greenhouse gas and sequester a significant quantity of carbon and thereby help in mitigation of climate change effects. There are several reports of carbon sequestration by oil palm in above ground biomass (Kongsager, Napier, & Mertz, 2013; Lamade & Bouillet, 2005) and in soil (Roslee, Rahim, & Idris, 2016; S. L. Singh, Sahoo, Kenye, & Gogoi, 2018; Suresh & Behera, 2014).

Understanding the dynamics of SOC helps in assessing ecosystem services and changes in soil properties (Bationo, Kihara, Vanlauwe, Waswa, & Kimetu, 2007; Lal, 2016; Nadal-Romero, Cammeraat, Perez-Cardiel, & Lasanta, 2016; Novara et al., 2017). There are different types of carbon fractions in soil based on SOC residence time (Rovira, Jorba, & Romanyà, 2010). The fractions of carbon especially of microbial origin and their derivative products having active recycling ability within a 5-year period are called the active carbon pool (ACP), whereas carbon fractions having longer residence time than that of the ACP are called the passive carbon pool (PCP). The ACP plays a vital role in soil nutrient availability and soil productivity, whereas the PCP has a higher carbon sink potential and contributes significantly toward soil productivity and sequestration of carbon (Mandal et al., 2008; Paul, Collins, & Leavitt, 2001; Sahoo, Singh, Gogoi, Kenye, & Sahoo, 2019; Torn, Vitousek, & Trumbore, 2005). Continuous land management for growing different crops affect SOC pools (Rudrappa, Purakayastha, Singh, & Bhadraray, 2006; Sherrod, Peterson, Westfall, & Ahuja, 2005; T. Wu et al., 2003). However, scarce information is available regarding different SOC pools of OPP of various ages *vis-à-vis* FL. Therefore, we hypothesized that there is variation in soil parameters including SOC pools and stocks of differently aged OPP and adjacent FL. The study was thus undertaken with the objectives: (a) to evaluate the soil properties and available nutrient status; and (b) to assess the different SOC pools and their stocks in differently aged OPP and adjacent FL of OPP. This information will be useful for devising future nutrient management strategies and gauging the sustainability of oil palm cultivation in the region.

2 | MATERIALS AND METHODS

2.1 | Study location

The study location was the research farm of ICAR-Indian Institute of Oil Palm Research (ICAR-IIOPR) located at Pedavegi of Andhra Pradesh State, India with geographical coordinates of 16.8102°N, 81.1065°E, and lying 22 m msl. The location has a hot-humid tropical climate and it receives the majority of the rainfall (mean rainfall is 950 mm) in June to September. The average temperature fluctuates from 23°C (during December) to 39°C (during May). The mean relative humidity ranges from 60% (during February) to 90% (during July and August). The soil of the site has developed from igneous and sedimentary formations and has a sandy clay-loam texture. It belongs to Entisol soil order (Soil Survey Staff, 2014).

The three OPP are located side-by-side (they are 6, 12, and 18 years-old) and also adjacent fallow land (FL) areas of the ICAR-IIOPR research farm were selected for study. The 18, 12, and 6 year-old plantations were established in a farm area and are each 3 ha their establishment was in 1998, 2004, and 2010, respectively. Oil palm plants were planted in equilateral triangular design (9 m × 9 m × 9 m) and were managed as irrigated crops. The site was lying uncultivated before the establishment of OPP. The plantations received uniform application of fertilizers. Each palm was supplied with 1,200 g N, 600 g P_2O_5, 1,200 g K_2O, and 500 g (16% MgO and 13% S), respectively, per year. The sources were CH_4N_2O (46% N), Ca $(H_2PO_4)_2$ (16% P_2O_5, 11% S, 20% Ca), and KCl (60% K_2O) for N, P_2O_5, and K_2O, respectively. The total amount of nutrients for each palm for a year was divided into four equal parts and added in four portions in the weed-free planting basin of the palm which had a 3 m radius. The fallow land was used for farm-related activities and it did not receive any irrigation and fertilizer application. The FL had natural vegetation of grasses and local leguminous species. The crop residue such as empty fruit bunches and chopped and pruned fronds generated at the time harvesting and root biomass were added to the palm basins.

2.2 | Collection of soil samples, processing, and analyses

A total of 264 composite soil samples were collected from three soil depths viz., 0–20, 20–40, and 40–60 cm (from 88 locations) during March and April of 2016 using a stainless-steel hand-held screw auger. The collection was from weeded palm basins (3 m radius) FL (22 locations) adjacent to OPP. For soil sampling, three quadrants of 250 m × 250 m were selected from representative sites of each OPP and in FL according to the sampling protocol outlined by S. Singh and Dadhwal (2009). The distance between any two quadrants varied from 40 to 60 m. Soil samples from quadrants in the OPP were collected from palm basins leaving 1 m distance from palm trunk (Rao et al., 2014). Soil samples were also collected from randomly selected points in quadrants of FL (fallow land). In order to get a composite sample of a location, three sub-samples were collected and mixed. The collected samples were processed by air-drying, removing debris and stones followed by grinding using mortar and pestle, and passing through a sieve (2 mm size). A sieve of 0.149 mm size was used for estimation of carbon pools. The soil properties such as pH [soil to water ratio of 1:2.5 (weight/volume)], electrical conductivity (EC) [soil to water ratio of 1:2.5 (weight/volume)], and SOC content were determined by the procedures proposed by Jackson (1973), Jackson (1973), and Walkley and Black (1934) (wet combustion method), respectively. Available N, available P, and available K status were measured by potassium permanganate (Subbiah & Asija, 1956), Olsen's (Olsen, Cole, Watanable, & Dean, 1954), and ammonium acetate (Hanway & Heidel, 1952) methods, respectively. Exchangeable Ca (Ex. Ca), exchangeable Mg (Ex. Mg), available S, and available B status were determined by ammonium acetate (Jones Jr., 1998), ammonium acetate (Jones Jr., 1998), calcium chloride (Williams & Steinbergs, 1969), and hot water (Gupta, 1967) methods, respectively.

The contents of ACP of SOC such as very labile and labile carbon and of PCP such as less labile carbon were estimated through modified Walkley & Black procedure (Chan, Bowman, & Oates, 2001). The very labile, labile, and less labile C pools were measured by using oxidation ability of 12, 18, and 24 N sulfuric acid, respectively, through different acid-aqueous solutions. Soil bulk density (BD) was estimated by digging soil pits (Robertson, Pope, & Tomlinson, 1974).The depth-wise stock of SOC was estimated through multiplying SOC content, soil depth, and BD (Blanco-Canqui & Lal, 2008; Parras-Alcántara, Lozano-García, Brevik, & Cerdá, 2015). Soil samples were dried at 105°C for 24 hr before measurement of SOC and estimation of BD. The SOC stock at each point of sampling was then scaled up to per hectare area of estimation (Mg ha^{-1}) (Khasanah, van Noordwijk, Ningsih, & Rahayu, 2015). The SOC stock for 0–60 cm depth was determined by summarizing SOC stock for all three soil depths, for differently aged OPP and FL of plantations.

$$\text{SOC stock} = (\text{SOC}/100) \times \text{soil depth} \times \text{BD} \times 10^4 \left(m^2/\text{ha}\right).$$

where: SOC stock in Mg ha^{-1}, SOC in %, depth of soil in m, BD of soil in Mg m^{-3}.

2.3 | Statistical analysis

Initially, the data regarding soil properties and available nutrients, different carbon pools, and SOC stocks were subjected to the tests of normality (using Shapiro–Wilk's test) and equality of error variances (using Levene's test) and verified. The two-way analysis of variance (ANOVA; age × depth) (Nath et al., 2018) through the procedure of generalized linear model (GLM procedure) [using SAS 9.2 software package (SAS, 2011)] was used to examine the effects of age of OPP and soil depth on studied soil parameters. The comparison between two means at probability level of 5% was undertaken through mostly acceptable Tukey's multiple compare test (Haynes, 2013). This test takes care of the statistical distributions attached with repetitive testing. It also provides an exact adjusted *p* value. To understand the correlations of soil properties and carbon pools, Pearson's correlation coefficient analysis was carried out. Further, principal component analysis (PCA) was performed to extract important information from the datasets and express the information through a set of new orthogonal variables. PCA focuses on the core structure of a single sample of observations on *p* variables, which are generally inter-correlated. The data suitability for PCA was checked using the Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity. The KMO tests the ratio of item correlations to partial item correlations and ranges from 0 to 1.0. The value of ≥0.50 is considered good for PCA. The Bartlett's test of sphericity checks for the hypothesis that the correlation matrix is an identified matrix. This means that all of the variables are uncorrelated. The significant value for this analysis led to rejection of the null hypothesis and concludes that there are correlations in the data that are appropriate for the PCA. The score from Bartlett's test of sphericity at probability level of 5% (significance at 95%) is considered appropriate for the PCA. Principal components (PCs) having eigenvalues more than one were considered (Jolliffe, 1986), since the values of correlation analysis were used.

3 | RESULTS

3.1 | Soil properties

The depth-wise distribution of soil properties of OPP and FL is presented in Table 1. Soil properties were significantly affected by soil depth and plantation age. Soil pH of OPP of different ages and AFL varied from 7.33 to 7.69, 7.10 to 7.45, and 7.04 to 7.42 at 0–20, 20–40, and 40–60 cm soil depth, respectively. At three soil depths, the FL had significantly lower pH, EC, exchangeable Ca and Mg, and available S values compared with pH, EC, exchangeable Ca and Mg, and available S values of OPP. There was no difference in available N and available K status in OPP and FL. The higher available P concentration was noted in three depths of soil of FL compared with that in OPP. However, available P concentration increased with OPP age and it was higher in 18 years-old OPP. The concentration of exchangeable Ca of differently aged OPP and FL ranged from 2.76–3.97, 2.44–3.86, and 2.62–4.00 meq 100 g^{-1} soil at 0–20, 20–40, and 40–60 cm depth, respectively. Whereas, exchangeable Mg concentration varied from 1.99–2.47, 1.93–2.47, and 2.07–2.40 meq 100 g^{-1} soil at 0–20, 20–40, and 40–60 cm depth, respectively. Available B concentrations in OPP of different ages and in FL did not differ. Soil parameters in different soil depths of OPP and FL did not show any consistent trend in distribution. The interaction effects between soil depth and OPP age were significant for all the soil properties except available N, available K, and available B.

3.2 | Soil organic carbon pools and their stocks

The SOC content in FL was less than SOC content in OPP at all the three soil depths (Table 2). The SOC contents in 0–20, 20–40, and 40–60 cm depth of OPP were higher by 25–68%, 28–41%, and 16–30%, respectively, compared with SOC in FL. The content of very labile C was higher in 0–20 cm soil depth under OPP compared with that in FL (Table 2). The labile and less labile C content under OPP and in FL in 0–20 cm depth were similar. The higher level of less labile C at all the three soil depths was recorded in OPP of 18 years old. SOC, ACP like very labile carbon and PCP like less labile carbon declined with increase in soil depth. There was significant interaction effect of soil depth and OPP age on soil organic pools. The SOC stock in 0–60 cm soil depth varied from 56.7 (in FL) to 82 Mg ha^{-1} (in 18 years-old OPP; Figure 1). Oil palm cultivation led to 20, 18, and 45% enhancement in SOC stock in 6, 12, and 18 years-old OPP, respectively, compared with SOC stock in FL. The stocks of very labile, labile, and less labile carbon in 0–60 cm depth varied from 27.1 to 31.7, 11.4 to 21.1, and 16.9 to 30.6 Mg ha^{-1}, respectively, under differently aged OPP and in FL (Figure 2). The very labile and less labile C stock in FL, 6 years-old and 12 years-old OPP were similar; whereas the values of these parameters were higher in 18 years-old OPP.

3.3 | Relationship of soil properties and soil organic carbon pools

There was negative correlation between soil pH and available K in 0–20 and 20–40 cm depth and between soil pH and available N and SOC in 0–20 cm depth (Table 3). In 40–60 cm depth, soil pH was positively correlated with very labile carbon and negatively with labile carbon. However, there was positive correlation of soil EC with Ex. Ca, SOC, and very labile carbon in 0–20 cm depth and with available K, available S, available B, SOC, and very labile carbon in 40–60 cm depth. Available N was positively correlated with available K, Ex. Ca, and very labile carbon in 0–20 cm depth, with Ex. Ca in 20–40 cm soil depth, and with very labile C in 40–60 cm soil depth. There was positive correlation between Ex. Ca versus available N and Ex. Ca versus available K in 0–20 cm depth, Ex. Ca versus available N, Ex. Ca versus available P and Ex. Ca versus available K in 20–40 cm depth and Ex. Ca versus available K in 40–60 cm soil depth. The SOC content was positively correlated with available P and with Ex. Ca in 0–20 cm depth, with Ex. Ca and available S in 20–40 cm soil depth and with three C pools

TABLE 1 Depth-wise distribution of soil properties in oil palm plantations of different ages

Soil depth	Age of plantation	pH	EC (dS m^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (meq 100 g^{-1} soil)	Mg (meq 100 g^{-1} soil)	S (mg kg^{-1})	B (mg kg^{-1})
0–20 cm	6 years	7.67 (0.10)^{a}	0.26 (0.01)^{a}	300 (12)^{a}	24.0 (3.26)^{d}	162 (19)^{a}	3.60 (0.19)^{a}	2.17 (0.25)^{a}	24.6 (1.59)^{a}	4.55 (0.45)^{a}
	12 years	7.69 (0.04)^{a}	0.23 (0.00)^{a}	303 (10)^{a}	30.3 (3.53)^{c}	151 (14)^{a}	3.22 (0.19)^{ab}	2.17 (0.22)^{a}	23.7 (2.39)^{a}	4.69 (0.38)^{a}
	18 years	7.60(0.15)^{ab}	0.27 (0.04)^{a}	294 (20)^{a}	42.9 (9.94)^{b}	168 (20)^{a}	3.97 (0.32)^{a}	2.03 (0.26)^{a}	28.5 (3.49)^{a}	5.49 (0.46)^{a}
	Fallow	7.33(0.22)^{b}	0.12(0.00)^{b}	271 (13)^{a}	51.5 (3.59)^{a}	189 (30)^{a}	2.76 (0.31)^{b}	1.79 (0.22)^{b}	15.1 (1.45)^{b}	5.33 (0.33)^{a}
	F value	*3.72*	*29.5*	*1.47*	*10.51*	*1.49*	*3.33*	*0.80*	*5.75*	*1.02*
	Prob. > F	*0.0144*	*<0.0001*	*0.2299*	*<0.0001*	*0.2233*	*0.0233*	*0.4996*	*0.0013*	*0.3862*
20–40 cm	6 years	7.45 (0.06)^{a}	0.22 (0.01)^{a}	275 (11)^{a}	18.6 (2.84)^{b}	162 (17)^{a}	3.36 (0.17)^{a}	2.14 (0.17)^{a}	24.0 (2.34)^{a}	3.87 (0.33)^{a}
	12 years	7.40 (0.04)^{a}	0.22 (0.00)^{a}	288 (11)^{a}	23.8 (2.54)^{b}	165 (13)^{a}	3.56 (0.19)^{a}	2.27 (0.18)^{a}	23.0 (2.91)^{a}	4.21 (0.35)^{a}
	18 years	7.31 (0.10)^{ab}	0.23 (0.01)^{a}	292 (15)^{a}	24.2 (4.79)^{b}	194 (32)^{a}	3.86 (0.19)^{a}	2.20 (0.40)$_{a}$	21.7 (2.17)^{a}	5.47 (0.87)^{a}
	Fallow	7.10 (0.21)^{b}	0.12 (0.00)^{b}	281 (14)^{a}	47.1 (2.69$^{)a}$	191 (27)^{a}	2.44 (0.24)^{b}	1.93 (0.22)^{b}	14.7 (3.22)^{b}	4.95 (0.23)^{a}
	F value	*4.83*	*26.52*	*0.29*	*19.71*	*0.59*	*7.34*	*1.40*	*2.37*	*2.77*
	Prob. > F	*0.0038*	*<0.0001*	*0.8299*	*<0.0001*	*0.6221*	*0.0002*	*0.2486*	*0.0759*	*0.0467*
40–60 cm	6 years	7.35 (0.06)^{a}	0.21 (0.01)^{b}	277 (19)^{a}	13.4 (1.29)^{b}	177 (15)^{a}	3.44 (0.12)^{a}	2.35 (0.22)^{a}	19.9 (1.95)^{a}	3.99 (0.32)^{a}
	12 years	7.29 (0.25)^{a}	0.23 (0.01)^{ab}	281 (13)^{a}	17.8 (2.27)^{b}	191 (20)^{a}	3.62 (0.15)^{a}	2.40 (0.20)^{a}	19.7 (1.43)^{a}	4.32 (0.34)^{a}
	18 years	7.42 (0.07)^{a}	0.27 (0.02)^{a}	277 (21)^{a}	20.8 (4.50)^{b}	206 (36)^{a}	4.00 (0.14)^{a}	2.07 (0.33)^{a}	19.6 (2.89)^{a}	4.04 (0.44)^{a}
	Fallow	7.04 (0.22)^{b}	0.12 (0.00)^{c}	283 (15)^{a}	41.6 (2.15)^{a}	203 (23)^{a}	2.62 (0.22)^{b}	2.12 (0.23)^{a}	14.2 (1.58)^{b}	5.04 (0.18)^{a}
	F value	*0.91*	*32.96*	*0.03*	*34.34*	*0.36*	*9.35*	*0.41*	*2.43*	*2.11*
	Prob. > F	*0.4374*	*<0.0001*	*0.9942*	*<0.0001*	*0.7820*	*<0.0001*	*0.7428*	*0.0705*	*0.1048*
Interaction (soil depth × age)		**	**	NS	**	NS	**	**	**	NS

Note: Values in parenthesis indicate standard error of means. Same letters in each column for a particular soil property and soil depth denote non-significance between two figures. ** Means significant; NS means non-significant.

Abbreviations: **, significant; B, available boron; Ca, exchangeable calcium; EC, electrical conductivity; K, available potassium; Mg, exchangeable magnesium; N, available nitrogen; NS, non-significant; P, available phosphorus; S, available sulfur.

TABLE 2 Depth-wise soil organic carbon (SOC), very labile, labile, and less labile carbon (C) pools in oil palm plantations of different ages

Soil depth	Age of plantation	SOC (%)	Very labile C (%)	Labile C (%)	Less labile C (%)
0–20 cm	6 years	0.74 (0.04)^{b}	0.32 (0.03)^{a}	0.20 (0.02)^{ab}	0.22 (0.02)^{b}
	12 years	0.75 (0.03)^{b}	0.30(0.02)^{a}	0.22 (0.02)^{a}	0.21 (0.02)^{b}
	18 years	0.99 (0.11)^{a}	0.41 (0.09)^{a}	0.17 (0.04)^{ab}	0.41 (0.08)^{a}
	Fallow	0.59 (0.03)^{c}	0.28 (0.02)^{b}	0.10 (0.01)^{b}	0.18 (0.02)^{b}
	F value	*8.97*	*1.28*	*3.68*	*5.30*
	Prob. > F	*<0.0001*	*0.2880*	*0.0151*	*0.0021*
20–40 cm	6 years	0.59 (0.03)^{a}	0.26 (0.02)^{a}	0.14 (0.02)^{a}	0.19 (0.03)^{b}
	12 years	0.60 (0.03)^{a}	0.22 (0.01)^{a}	0.18 (0.02)^{a}	0.19 (0.02)^{b}
	18 years	0.65 (0.06)^{a}	0.22 (0.04)^{a}	0.19 (0.03)^{a}	0.24 (0.04)^{a}
	Fallow	0.46 (0.02)^{b}	0.22 (0.01)^{a}	0.08 (0.01)^{b}	0.15 (0.01)^{b}
	F value	*5.19*	*0.86*	*4.15*	*1.11*
	Prob. > F	*0.0025*	*0.4628*	*0.0086*	*0.3483*
40–60 cm	6 years	0.44 (0.02)^{a}	0.19 (0.01)^{a}	0.13 (0.02)^{a}	0.12 (0.01)^{b}
	12 years	0.43 (0.01)^{a}	0.19 (0.01)^{a}	0.14 (0.01)^{a}	0.12 (0.01)^{b}
	18 years	0.48 (0.05)^{a}	0.19 (0.02)^{a}	0.13 (0.04)^{a}	0.18 (0.03)^{a}
	Fallow	0.37 (0.02)^{b}	0.19 (0.01)^{a}	0.09 (0.01)^{b}	0.09 (0.01)^{b}
	F value	*2.62*	*0.02*	*1.39*	*2.95*
	Prob. > F	*0.0560*	*0.9947*	*0.2519*	*0.0373*
Interaction (soil depth × age)		**	**	**	**

Note: Values in parenthesis indicate standard error of means. Same letters in each column for a particular soil property and soil depth denote non-significance between two values. ** Means significant.

in all the three depths. It was also positively correlated with studied C pools in all the three depths.

PCA resulted in five principal components (PCs) with eigenvalue >1 and accounting for more than 60% of total variance (Table 4). PC1, PC2, PC3, PC4, and PC5 explained 23.98, 12.92, 11.25, 9.41, and 7.70% of total variance, respectively, in 0–20 cm depth, 21.18, 12.29, 11.85, 10.11, and 8.55% of total variance, respectively, in 20–40 cm depth and 19.03, 14.08, 12.28, 10.31, and 9.22% of total variance in 40–60 cm depth, respectively. In 0–20 cm depth, PC1 was dominated by very labile carbon, SOC, Ex. Ca, EC and available N, available P, and available K, whereas pH, EC, labile carbon, and less labile carbon had significant effect on PC2. PC1 was dominated by Ex. Ca, SOC and available K and S in 20–40 cm soil depth, whereas less labile, labile, and very labile carbon played significant role in PC2. In 40–60 cm soil depth, soil parameters like EC, available S, and available B and very labile carbon led PC1 and less labile and very labile carbon, available K, and pH led PC2. PC1 and PC2 biplot analysis revealed two main assemblages of soil parameters in all the three soil depths (Figure 2) although there was variation in group members in different depths.

4 | DISCUSSION

4.1 | Soil properties

The assessment of soil parameters is necessary to find out the effect of different land management practices and subsequent improvement. We recorded higher soil pH and EC in OPP than FL (Table 1). The higher soil pH and EC values in OPP are attributed to accumulation of ions and salts in soils because of root-biomass and added crop residue mineralization and adoption of plantation management practices (Carmo, Lima, & Silva, 2016). Increase in soil pH due to crop residue addition is attributed to decarboxylation of organic acid anions causing proton consumption and release of OH^{-}ions, specific adsorption of organic molecules released during decomposition onto Al and Fe hydroxides with release of OH^{-} ions and higher concentration of base cations in crop residue (Butterly, Baldock, & Tang, 2013; Mokolobate & Haynes, 2002). Sometimes, ammonification of residue-nitrogen causes consumption of H^{+} ions, if not accompanied by strong nitrification. The increase in available P concentration with the age of OPP (Table 1) is probably due to application of higher amount of P fertilizer relative to P use by OPP. This could also be due to increased recycling and bioavailability of native soil P with increase in plantation age (H. Wu et al., 2019). The higher concentration of available P has also been reported in some cultivated soils of India (Sanyal et al., 2015), European Union (Toth, Guichamaud, Toth, & Hermann, 2014), and USA (L. K. Sharma, Bali, & Zaeen, 2017) due to continued application. This warrants rationalization in P fertilizer use in these plantations according to soil P availability, soil pH, and crop requirement. The higher concentration of available P in FL is probably due to P mobilization from unavailable soil pools by the natural vegetation of grasses and local leguminous species and its return to soil as fallow biomass (Kamh, Horst, Amer, Mostafa, & Maier, 1999; Kolawole, Tian, & Tijani-Eniola, 2005). The higher concentration of exchangeable Ca, Mg, and

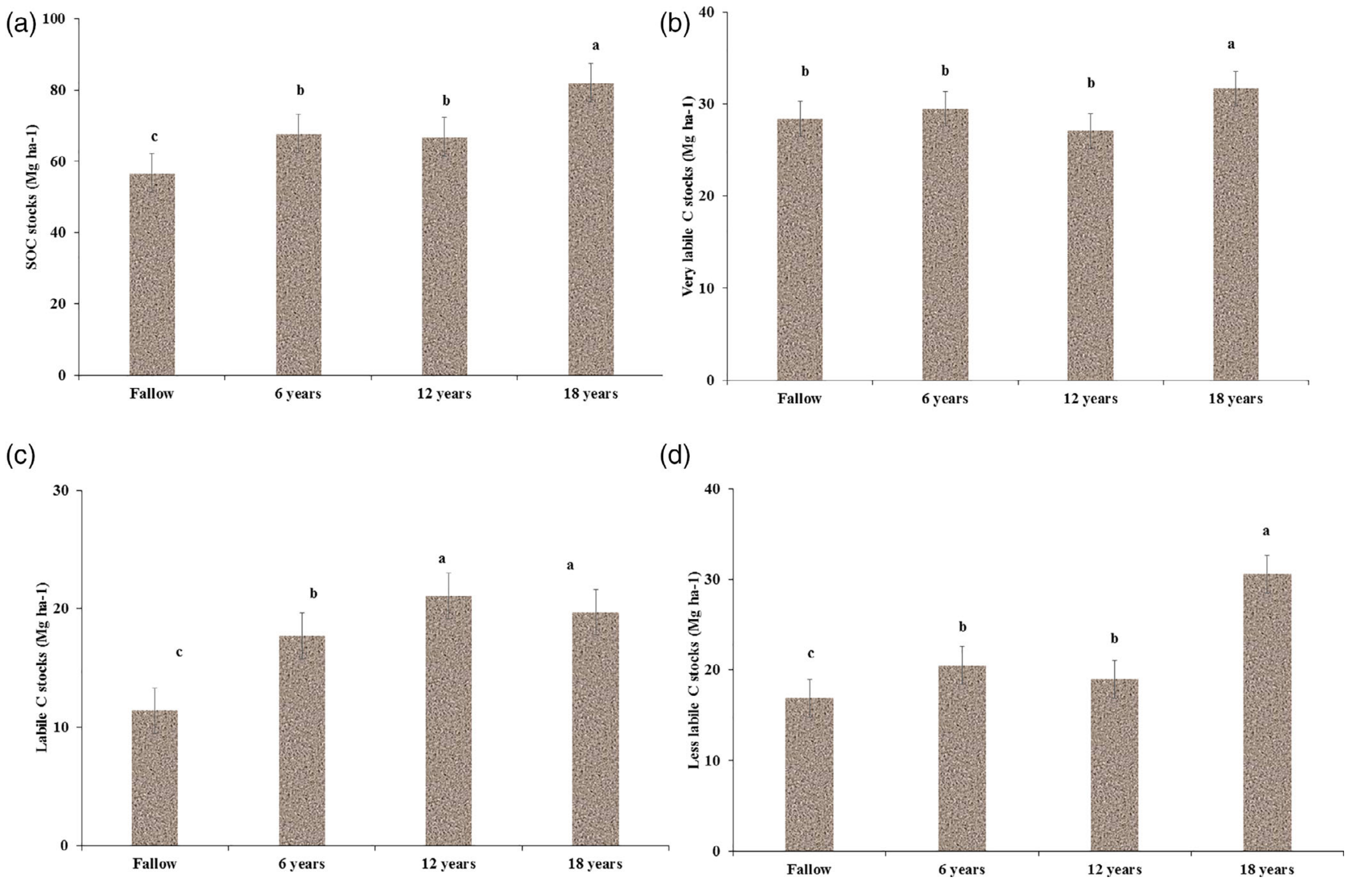

FIGURE 1 Differences in stocks (Mg ha^{-1}) SOC, very labile, labile, and less labile C in oil palm plantations of different ages and in fallow land in 0–60 cm soil depth. Error bars indicate standard error of means. Same letters in for a particular soil parameter and soil depth denote non-significance between two values [Colour figure can be viewed at wileyonlinelibrary.com]

available S in OPP compared with FL may be due to continuous addition these nutrients through fertilizers for plantation management, addition from crop residue mineralization, and low uptake compared with addition. But the concentration of these nutrients did not increase with increasing age of OPP. This could be due to increased nutrient uptake and accumulation in different plant parts of oil palm with increasing age (Ng, 2002; Tinker & Smilde, 1963). While investigating the variations in soil parameters of differently aged teak plantations of Myanmar's Bago Mountain, Suzuki, Takeda, and Thein (2007) recorded increase in exchangeable Ca in surface soils with increasing age of teak plantations, whereas Oku, Iwara, and Ekukinam (2012) observed no change of pH, N content, and reduction of soil micronutrient status with the increasing age of rubber plantations grown on Ultisols of the humid forest zone, Nigeria. However, Ramamurthy et al. (2016) observed an increased concentration of available nutrients with increased ages of *Eucalyptus citriodora* plantations of semi-arid region of Karnataka, India. Increasing year of cultivation of cacao in natural and traditional agroforestry management systems of Peru led to decrease in exchangeable K and Mg in soils (Arévalo-Gardini et al., 2015). But the change was more apparent in 0–20 cm soil depth. In our study, no consistent trend in distribution of soil parameters with soil depth in OPP and FL was recorded. K. L. Sharma et al. (2009) also recorded an inconsistent trend in depth-wise distribution of pH, exchangeable Ca, Mg and K and total N, P, and K in Alfisol of a tree crop-based land use system in the semi-arid tropical region of India.

4.2 | Soil organic carbon pools and their stocks

The differently aged OPP had higher SOC compared with SOC in FL in different depths (Table 2). The highest SOC content was recorded in 18 years-old OPP. The higher SOC content in OPP is mainly attributed to continuous addition and decomposition of significant quantity of crop residue such as empty fruit bunches and pruned fronds and root biomass to soil as a source of C. Oil palm produces substantial amount of root biomass especially fine roots (Khalid, Zin, & Anderson, 1999; Suresh, Reddy, Sarma, Bhanusri, & Sivasankar Kumar, 2003; Violita, Triadiati, Anas, & Miftahudin, 2016), which increases with the age of plantations (Smith et al., 2012). Brahma et al. (2017) also recorded higher SOC in rubber plantations in India developed on degraded soil. The low SOC content in FL is because of less organic matter addition by low vegetation cover. However, SOC content in both OPP and FL declined with increase in soil depth. Wynn, Bird, and Wong (2004) also

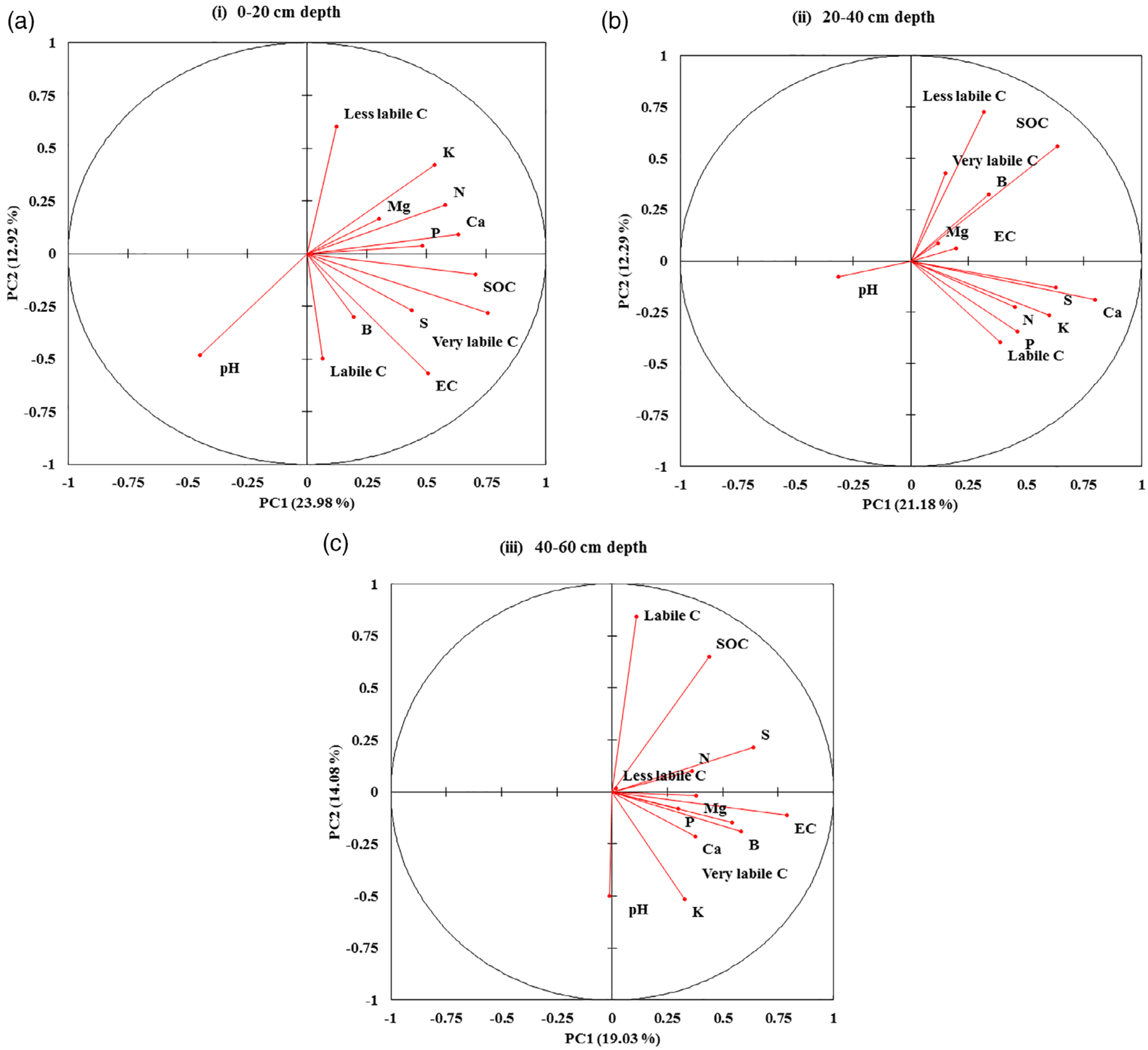

FIGURE 2 Bi-plots (PC1 vs. PC2) of soil parameters in different soil depths [Colour figure can be viewed at wileyonlinelibrary.com]

noted reduction in SOC with soil depth. Higher SOC content in surface soil layer may be due to the fact that bulk of organic matter added or contributed by plantation crops are located in surface soil (Sharma et al., 2009). The depth-wise SOC distribution is also influenced by intrinsic soil properties and land management practices (Hobley & Wilson, 2016). There was a variation in SOC pools due to the effect of age of OPP at different soil depths. Increase in less labile carbon under 18 years-old OPP is in coherent with the observations of enhancement in SOC pools with increasing spruce stand age in the eastern Tibetan Plateau by Q. Liu, Zhao, Cheng, and Yin (2015). It is attributed to the decomposition of added root biomass over the years. Like our findings, the changes in carbon pools due to carbon input through crop residue, root biomass and by following different crop management practices over the period of time have been recorded by different researchers (Conant, Six, & Paustain, 2003; Sherrod et al., 2018; T. Wu et al., 2003). Nath et al. (2018) recorded changes in SOC pools under various land uses such as grassland, natural forest, and rubber plantations of different ages in Assam State, India. The variations of SOC pools because of varied land utilization pattern were also recorded for soils of Bavaria, Germany and for Vertisols of India (Jha et al., 2012; Wiesmeier et al., 2014). The variation of soil carbon pools is attributed to OPC, soil management practices and its influence on soil physico-chemical properties modifying soil carbon reserve (Adger & Brown, 1994; Hossain, Jusoh, & Fatimah, 2017; Ogeh & Osiomwan, 2012). In our study, the very labile and labile carbon pools in differently aged OPP were similar which revealed no effect of plantation age on these carbon pools. However, the higher content of SOC and less labile carbon pool in 18 years-old OPP compared with that in 6 and 12 years-old OPP in the present study indicates better soil fertility, short-term land use sustainability, and the ability to alleviate

TABLE 3 Relationship among studied soil properties and SOC pools in oil palm plantations at different soil depths

	pH	EC	N	P	K	Ca	Mg	S	SOC	Very labile C	Labile C
0–20 cm											
N	−0.265*	0.062	1.000								
K	−0.515**	0.152	0.314*	0.127	1.000						
Ca	−0.059	0.270*	0.408**	0.161	0.376**	1.000					
SOC	−0.271*	0.288*	0.236	0.278*	0.144	0.337**	0.036	0.187	1.000		
Very labile C	−0.189	0.460**	0.337**	0.342**	0.105	0.404**	0.171	0.306*	0.595**	1.000	
Labile C	−0.046	0.188	−0.092	−0.048	−0.022	−0.076	−0.138	0.074	0.372**	−0.104	1.000
Less labile C	−0.138	−0.256*	0.050	0.067	0.110	0.108	−0.013	−0.130	0.444**	−0.148	−0.240
20–40 cm											
K	−0.300*	0.017	0.194	0.273*	1.000						
Ca	−0.122	0.232	0.385**	0.360**	0.444**	1.000					
S	−0.038	0.146	0.136	0.289*	0.264*	0.508**	0.006	1.000			
SOC	−0.143	0.031	0.138	0.051	0.207	0.290*	0.015	0.259*	1.000		
Very labile C	−0.059	0.156	0.121	0.033	−0.083	0.081	−0.036	0.164	0.294*	1.000	
Labile C	−0.047	−0.034	0.160	0.106	0.206	0.216	0.039	0.169	0.381**	−0.408**	1.000
Less labile C	−0.088	−0.056	−0.076	−0.063	0.134	0.095	0.012	0.032	0.659**	−0.065	−0.126
40–60 cm											
K	0.014	0.247*	0.124	0.165	1.000						
Ca	0.053	0.233	0.027	0.087	0.273*	1.000					
S	−0.133	0.446**	0.221	0.102	0.078	0.127	0.047	1.000			
B	0.070	0.428**	0.047	0.066	0.132	0.208	0.356**	0.264*			
SOC	−0.041	0.250*	0.135	0.031	−0.137	0.002	−0.027	0.243	1.000		
Very labile C	0.259*	0.356**	0.259*	0.182	0.099	−0.025	0.080	0.203	0.380**	1.000	
Labile C	−0.312*	0.021	−0.043	0.087	−0.264*	0.036	−0.015	0.166	0.553**	−0.225	1.000
Less labile C	0.101	0.018	0.018	−0.231	0.043	−0.020	−0.092	−0.037	0.424**	−0.063	−0.252*

Note: * and ** denote significance of correlation coefficient at $p < .05$ and $p < .01$.
Abbreviations: B, available boron; C, carbon; Ca, exchangeable calcium; EC, electrical conductivity; K, available potassium; Mg, exchangeable magnesium; N, available nitrogen; P, available phosphorus; S, available sulfur; SOC, soil organic carbon.

climate change effect by C sequestration. Ishizuka et al. (2005) recorded little variation in SOC contents of 5 and 15 years-old OPP of Jambi Province, Indonesia. In the present study, the higher SOC content in 18 years-old OPP is ascribed to addition of increasing amount of root biomass with increase in age of OPP (Syahrinudin, 2005).

We noted higher SOC stock in differently aged OPP compared with SOC stock in FL (Figure 1). In agreement to our findings, several researchers recorded enhanced SOC stock in poplar and rubber plantations of different ages compared with SOC stock in agricultural/fallow land (Maggiotto et al., 2014; Nath et al., 2018; Sierra, Martínez, Verde, Martín, & Macías, 2013). In OPP, enhanced stock of SOC is attributed to higher C sequestration due to addition of crop residue and adoption of good crop management practices producing better root biomass as the subsequent decomposition of oil palm root contribute to SOC (Lamade & Bouillet, 2005). The quality and quantity of litter material influence population and activity of soil microbes, which affect SOC (Vesterdal, Schmidt, Callesen, Nilsson, & Gundersen, 2008). We recorded the higher SOC stock in 18 years-old OPP compared with SOC stock in 6 and 12year-old OPP. Several other studies reported SOC stock build-up over a period due to conversation of forest and non-forest lands into OPP (Bruun, Egay, Mertz, & Magid, 2013; Hergoualc'h & Verchot, 2011; Rahman et al., 2018; Tanaka et al., 2009). However, Khasanah et al. (2015) recorded no change in SOC stock of top 30 cm soil due to age of forest and non-forest derived OPP, which was ascribed to balance between decline of SOC from earlier vegetation and build-up of SOC due to OPP. The higher SOC stock in 18 years-old OPP is probably because of good management practices leading to net recovery of SOC due to decomposition of added crop residue and root biomass over a period (Khasanah et al., 2015). Additionally, increase in SOC may be due to reduced soil respiration with ages of plantations (Saiz et al., 2006), because soil respiration is one of the important factors of carbon balance contributing predominantly toward respiration of ecosystem (Tedeschi et al., 2006).

TABLE 4 Principal component analysis loadings for various soil parameters at different soil depths

Variables	0–20 cm					20–40 cm					40–60 cm				
	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5	PC1	PC2	PC3	PC4	PC5
pH	**−0.449**	**−0.482**	0.039	**−0.539**	−0.024	−0.314	−0.076	0.276	0.316	**0.668**	−0.013	−0.501	**0.526**	0.351	−0.084
EC	**0.506**	**−0.566**	−0.157	0.067	−0.049	0.198	0.061	**0.601**	0.299	0.191	**0.789**	−0.113	0.057	0.142	−0.131
N	**0.580**	0.232	−0.049	−0.182	**−0.421**	**0.452**	−0.223	0.073	−0.254	−0.256	0.359	0.102	−0.027	**−0.568**	**0.485**
P	**0.484**	0.037	0.067	−0.198	0.322	**0.461**	−0.345	0.190	−0.058	0.017	0.297	−0.081	−0.199	**0.617**	0.226
K	**0.533**	**0.421**	−0.210	0.348	−0.359	**0.600**	−0.264	−0.253	−0.163	−0.058	0.326	**−0.515**	−0.089	−0.041	−0.078
Ca	**0.632**	0.092	−0.071	−0.239	−0.302	**0.799**	−0.190	0.192	−0.003	0.043	0.375	−0.214	−0.235	0.061	**−0.485**
Mg	0.303	0.165	**−0.530**	0.078	**0.441**	0.117	0.085	0.307	**0.638**	−0.285	0.380	−0.016	**−0.445**	−0.427	0.037
S	**0.439**	−0.268	−0.314	−0.054	0.165	**0.628**	−0.130	0.222	−0.088	0.322	**0.639**	0.215	−0.038	0.032	0.024
B	0.195	−0.300	**0.467**	−0.211	−0.329	0.338	0.326	0.255	0.356	**−0.506**	**0.580**	−0.192	−0.206	−0.100	−0.334
SOC	**0.704**	−0.098	**0.572**	0.142	0.277	**0.637**	**0.560**	−0.306	0.042	0.268	**0.439**	**0.650**	**0.540**	0.039	−0.100
Very labile C	**0.755**	−0.280	−0.050	−0.260	0.158	0.149	**0.428**	**0.540**	**−0.550**	0.077	**0.542**	−0.147	**0.436**	0.111	**0.555**
Labile C	0.066	**−0.498**	0.293	**0.717**	−0.036	0.387	−0.397	**−0.460**	**0.416**	0.157	0.109	**0.843**	−0.211	0.307	−0.172
Less labile C	0.122	**0.602**	**0.606**	−0.147	0.253	0.315	**0.727**	−0.395	0.112	0.125	0.016	0.019	**0.666**	**−0.433**	**−0.431**
Eigenvalue	3.118	1.680	1.463	1.223	1.001	2.753	1.597	1.541	1.314	1.112	2.474	1.830	1.597	1.340	1.199
Explained variance (%)	23.982	12.925	11.250	9.407	7.702	21.180	12.288	11.855	10.109	8.556	19.032	14.077	12.282	10.308	9.222
Cumulative variance (%)	23.982	36.907	48.157	57.564	65.266	21.180	33.467	45.323	55.431	63.987	19.032	33.109	45.391	55.699	64.922

Abbreviations: B, available boron; Ca, exchangeable calcium; EC, electrical conductivity; K, available potassium; Mg, exchangeable magnesium; N, available nitrogen; P, available phosphorus; S, available sulfur; SOC, soil organic carbon.

4.3 | Relationship of soil properties and soil organic carbon pools

We recorded negative correlation of soil pH with available N, available K, and SOC in surface soil layers (Table 3) in contrast to the positive correlation between soil pH and EC and between soil pH and Ex. Mg in oil palm plantations of southern India as noted by Behera et al. (2018). Soil pH influences nutrient availability as hydrogen ions displace nutrients from negatively charged soil surfaces and the effect depends upon the charge and size of nutrient molecules. According to Corwin and Lesch (2005), soil EC indirectly indicates available nutrients and soil salinity levels and this is proposed as proxy estimation for various soil parameters such as soil texture, cation exchange capacity, organic matter content, salt concentration, water holding capacity, and drainage condition. We also recorded positive correlation of EC with majority of soil parameters in 0–20 and 40–60 cm depth of soil. Positive correlation between available N and very labile C signifies the role of labile C as source of energy during nitrogen mineralization and estimation of labile C for prediction of nitrogen mineralization. Positive correlation of SOC with available P and Ex. Ca in surface soil layers signifies the increase in concentration of available P and Ex. Ca with increase in SOC. SOC is the vital component of soil organic matter (SOM) and it influences soil properties, storage, and phytoavailability of nutrients. SOM is important for soil quality improvement. Upon decomposition, SOM releases various organic acids, which modifies soil environment favorably. Positive correlation of SOC with studied soil carbon pools has also been documented by various researchers in different soil-crop situations (Liang et al., 1997; E. Liu, Yan, Mei, Zhang, & Fan, 2013; Rudrappa et al., 2006). The SOC and studied pools are interrelated properties and these are sensitive indicators to monitor SOM change. The technique of multivariate analysis viz., PCA of studied soil parameters exhibited five PCs having different association patterns with soil parameters in three depths of soil (Table 4). Biplot analysis of PC1 and PC2 showed two clusters of soil parameters (Figure 2). Several other researchers have also analyzed soil properties using PCA to find out relationship among them (Fox & Metla, 2005; Islabao, Pinto, Selau, Vahl, & Timm, 2013; Visconti, de Paz, & Rubio, 2009).

5 | CONCLUSIONS

The present study revealed the impact of OPC on soil properties, available nutrients, and SOC pools and their stock. The OPP with given management practice had higher soil pH, EC, Ex. Ca, Ex. Mg, and available S compared with FL. The concentration of available P increased with age of OPP. The 18year-old OPP recorded higher content of SOC, less labile C, and SOC stock. Studied soil parameters were differently correlated with each other with two major groupings (PC1 and PC2) in all the three soil depths. This knowledge could be used in further assessing the sustainability of oil palm cultivation long-term basis and deciding nutrient management options in the present and similar study areas. Moreover, there is need for evaluating the soil properties and pools and stocks of SOC in different agricultural and other horticultural land utilizations *vis-a-vis* those soil parameters in oil palm plantations on a long-term basis for taking decisions that aim to promote a correct and sustainable land use system.

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ORCID

Sanjib K. Behera https://orcid.org/0000-0003-1105-6782
Arvind K. Shukla https://orcid.org/0000-0001-7867-8717

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