Conversion of forest to cinnamon plantation depletes soil carbon stocks in the top metre of the tropical highlands of Kerinci Regency, Jambi Province, Indonesia

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Conversion of forest to cinnamon plantation depletes soil carbon stocks in the top metre of the tropical highlands of Kerinci Regency, Jambi Province, Indonesia

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Abstract

This study aimed to investigate the effect of conversion from natural forest to cinnamon plantation on the top 1 m soil carbon stocks and soil characteristics. The project was conducted on Andosols of Kerinci Regency, Sumatera, Indonesia, sampling the soil profile under natural forests and a chronosequence of cinnamon plantations of different ages (1, 5 and 10 years). SOC stocks were quantified alongside physical properties (bulk density) and chemical properties (carbon, nitrogen, C/N ratio) to investigate the impact of land conversion. SOC stocks increased 1 year after conversion to cinnamon plantations, but then tended to decrease as the plantations got older. The initial increase was observed alongside decreasing bulk density 1 year after forest conversion to cinnamon plantation, likely as a result of the fresh input of (less dense) pyrogenic soil organic matter as a result of slash and burn practices and transport down the soil profile owing to leaching. In older plantations SOC stocks were lower, probably because organic matter had been decomposed or leached out of the profile. The free particulate organic matter (fPOM) was isolated from selected topsoil and subsoil layers and analysed for carbon, nitrogen, and FTIR analysis. FTIR analysis revealed that topsoil fPOM contained more aromatic functional groups than subsoils and had a higher degree of decomposition. Aromatic and carbohydrate functional groups were initially lower in recently converted cinnamon plantation, but the trend was reversed 10 years after conversion. The initial flush of fresh organic matter into soils after slash and burn provides fPOM with a lower degree of decomposition but is short-lived and fPOM becomes more microbially processed as the cinnamon plantation ages. We conclude that, after a short term increase brought about by slash and burn, forest conversion to cinnamon plantation in Kerinci Regency depletes SOC stocks both in topsoils and subsoils.

KEYWORDS

decomposition, land use, plantation, soil organic carbon, stocks

1 | INTRODUCTION

It is evident that soil physical, chemical, and biological processes, influencing soil health, quality, and productivity are regulated by soil organic carbon (SOC) (Lal, 2004a, 2015). At 1 m depth, soils contain approximately 1500 Gt of organic carbon globally (Lal, 2017). However, soil has become one of the most significant contributors to increasing atmospheric CO_2 concentrations, mainly because of land use change for agriculture (Hendrickson, 2012; Lal, 2004a, 2004b). The cumulative historic global loss of carbon because of land use change between 1750 and 2015 has been estimated at 190 ± 65 Pg C (including losses from both soil and vegetation), which compares with 410 ± 20 Pg C emitted over the same period owing to fossil fuel combustion (Le Quéré et al., 2016).

Shifting cultivation practices, particularly in Southeast Asia, have been practised for thousands of years. Still, recent demographic pressures have reduced the duration of fallow periods, decreasing the system's sustainability (Smith et al., 2016). Land use change from native vegetation to cash crop vegetation results in SOC loss (Lal, 2004a) as a result of greater decomposition rates (Yuste et al., 2007). Land conversion elevates soil temperature by opening soils to sunlight and increases the decomposition rate of both labile and persistent organic matter fractions (Fang et al., 2005; Kirschbaum, 1995). Downward movement of dissolved organic carbon through the soil profile owing to precipitation (Kaiser & Kalbitz, 2012) and deep root penetration of new plants releases root exudates that can also prime the decomposition of carbon buried deep within the soil profile by providing microorganisms with a fresh carbon source that they can use to co-metabolize deep SOC (Bernal et al., 2016; Fontaine et al., 2007). The subsoil (below 30 cm) contains the largest SOC pool because of its high capacity to protect SOC from decomposition (Six et al., 2002). However, despite the considerable importance of subsoil SOC, our understanding of the factors influencing subsoil SOC dynamics and how subsoil SOC stocks are altered by changing land use is still limited (Gross & Harrison, 2019; Rumpel & Kögel-Knabner, 2011).

Soils in Indonesia have been, and continue to be, exploited intensively for agriculture, mostly after conversion from natural forest. Around 877,000 acres of forest are cleared annually for agricultural use and urban development (Tölle, 2020). However, the true magnitude of SOC depletion caused by this deforestation and the potential to reverse the trend of carbon emissions and increase carbon storage using the available range of land management strategies have not yet been fully and systematically quantified (Minasny et al., 2017). Hairiah et al. (2001) showed that conversion of forest to rubber plantations decreases soil C stocks from 55 to 40 Mg C ha^{-1} and a more recent study by van Straaten et al. (2015) found that conversion of natural forest to rubber, oil palm, and cacao plantation in Jambi Province, Sumatera decreases the topsoil carbon stock by up to 50%.

In Indonesia, particularly in the Kerinci Regency of Jambi Province, Sumatera, shifting cultivation practices now occur less frequently, but there has been an increase in cinnamon (*Cinnamomum burmanii* [Nees & T. Nees] Bl.) agroforestry plantations because of the high economic value of cinnamon on global markets (Hariyadi & Ticktin, 2012). Cinnamon (also called cassiavera or cassia) has become one of the most important agricultural commodities produced in Indonesia. Indonesia contributes 66% of worldwide cinnamon supply. 85% of Indonesian cinnamon originates from Jambi Province, most of which is grown in plantations in Kerinci Regency. Moreover, cinnamon products from Kerinci Regency have a reputation for being high quality (known as *Korintji* Cinamon) because of their many superiorities, including aroma, flavour, colour, size, shape, and high essential oil content (Lizawati et al., 2016).

Based on data from the Statistics Office of Kerinci Regency (BPS, 2018), almost all cinnamon plantations in Kerinci Regency are managed by local farmers employing agroforestry cropping systems, which are estimated to cover about 40,762 Ha (12.25% of the total regency area). Thus, cinnamon plantations in Kerinci Regency are still managed by smallholder farmers to suppliment their income (Lizawati et al., 2016). However, expansion of these plantations is leading to extensive deforestation within the natural forest area surrounding the Kerinci Seblat National Park (Hariyadi & Ticktin, 2012). The impact of this land conversion from natural forest to cinnamon plantation on the soil carbon stocks is unknown.

We quantified SOC stocks down the soil profile under cinnamon plantations of different ages in three locations in Kerinci Regency, Jambi Province, Indonesia. We collected soil cores at 10 cm intervals down the soil profile (to 1 m) to calculate total stocks of SOC under these land uses and to investigate the effect that natural forest conversion to cinnamon plantation has on topsoil and subsoil carbon. We then investigated whether the chemical composition (quality) of soil organic matter (SOM) changes at selected depths in topsoil and subsoil and whether this was different under different land uses. Our aim was to measure topsoil and subsoil carbon stocks in soils under different ages of cinnamon plantation in Kerinci Regency, Sumatera, Indonesia and compare with SOC stocks under native forest. We hypothesised that topsoil and subsoil carbon stocks would decrease with age of cinnamon plantation, and that SOC would decrease with depth. We hypothesised that there would be greater degradation of SOC in soils converted to cinnamon plantations, as reflected in the chemical quality of topsoil and subsoil SOM.

2 | METHODOLOGY

2.1 | Study sites and soil sampling

Our study area was in the Kerinci Regency, Jambi Province of Indonesia, located in the highest elevation land of Jambi Province. The regency is situated between 1° 40′ and 2° 4' S, 101° 8′ and 101° 50′ E, surrounded by Kerinci Seblat National Park and Kerinci Mountain. The elevation of the sampling sites ranged from 1000 to 1500 m above sea level. Mean annual temperature is 22.9°C (ranging from 28.9–18.6°C) and mean annual precipitation is 2991 mm, with the dry season occurring for less than 2 months per year (BPS, 2018). Three villages were selected following Lizawati et al. (2016) because they were identified as major cinnamon producing areas in Kerinci Regency. These villages were Lempur, Pungut, and Renah Kayu Embun (RKE) villages (Figure 1).

At each village soil samples were collected from four sites. These four sites included one patch of natural forest and three cinnamon plantations that were 1, 5, and 10 years old. We adopted a random stratified sampling strategy. Samples were collected by digging a soil pit at each site and collecting a core every 10 cm down the soil profile to 1 m using a 176.63 cm^3 bulk density ring (height = 4 cm, diameter = 7.5 cm). At each 10 cm depth increment we also collected a second soil sample for chemical analysis.

Bulk density, carbon, and nitrogen were analysed for each soil sample taken at 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm. Free particulate organic matter (fPOM) was obtained at two selected depths representative of topsoil (0–10 cm and 20–30 cm) and two selected depths representative of the subsoil (50–60 cm and 90–100 cm) and analysed with FTIR to assess soil organic matter quality in topsoil and subsoil.

2.2 | Laboratory analysis

2.2.1 | Bulk density, carbon, nitrogen and carbon stocks

Bulk density of each soil layer was measured on an oven-dry basis by weighing the contents of each ring after drying at 105°C for 24 h. Soil samples collected alongside bulk density rings were air dried and sieved through a 2 mm screen prior to further analysis. Carbon and nitrogen were analysed by dry combustion methods using a Thermo Flash 2000 C/N analyser. Each duplicate subsample was ground to a fine powder using a ball mill, and 10 mg weighed into a tin cup before analysis. 24 replicates of an in-house QC material that is traceable to GBW07412 (certified for N

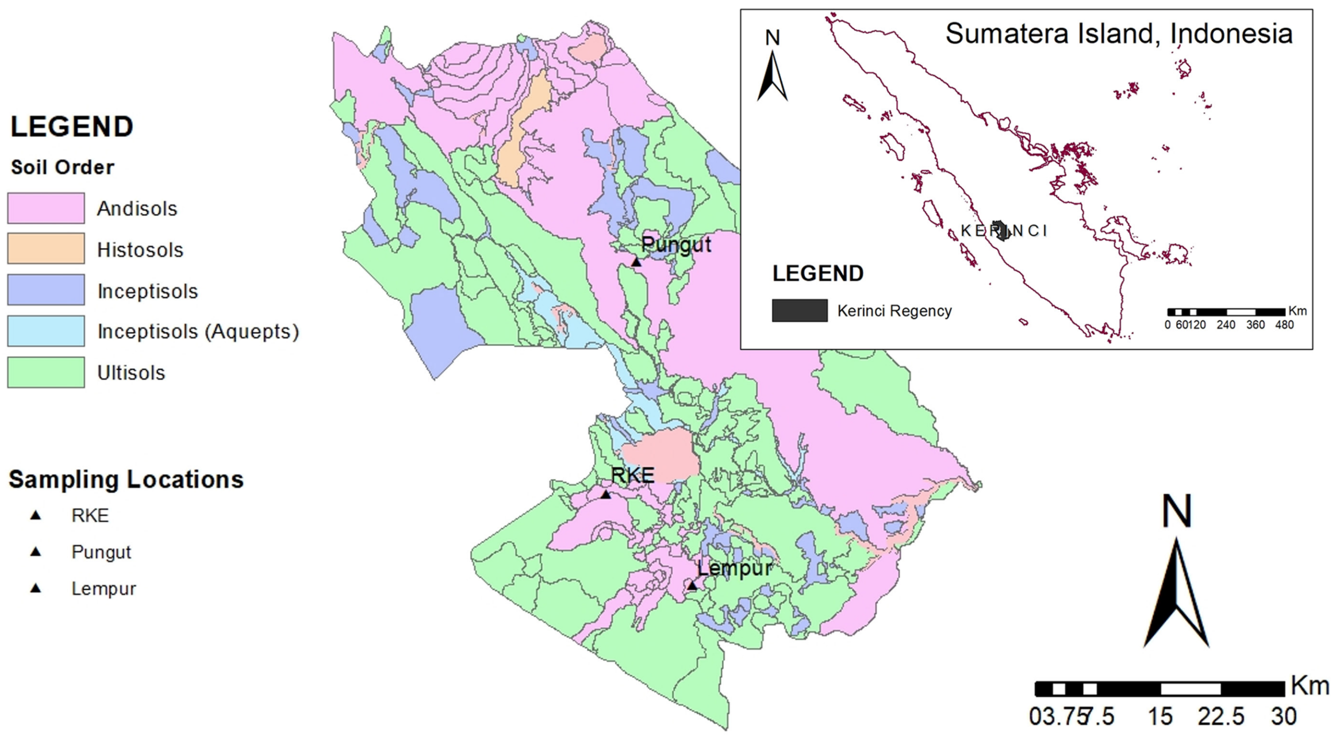

FIGURE 1 The three sampling sites, located in the villages of Lempur, Pungut, and Renah Kayu Embun (RKE) in Kerinci Regency, Jambi Province, on the Indonesian Island of Sumatra, overlain on a soil map of the Regency (source: Department of Agriculture, Indonesia).

by State Bureau of Technical Supervision, The People's Republic of China) and AR-4016 (certified for C by Alpha Resources Inc. with ISO 17025 accreditation) were run alongside samples with recoveries of 98.15% ± 0.007 and 100.16% ± 0.030 for N and C, respectively.

We calculated SOC stocks in each 10 cm soil layer following Guo and Gifford (2002), using the following equation:

$$Ct = BD \times SOC \times D$$

Where Ct is the SOC stock (Mg ha^{-1}), BD is the soil bulk density (g m^{-3}), SOC is the soil carbon concentration (%), and D is the soil sampling thickness (10 cm). The stocks for each 10 cm soil layer were summed to calculate the carbon stock in Mg ha^{-1} to a depth of 1 m and for topsoil (0–30 cm) and subsoil (30–100 cm).

2.2.2 | Free particulate organic matter isolation

Free particulate organic matter (fPOM) was obtained by extracting a quantity of air-dried 2 mm sieved soil that was mixed with 80 mL of 1.85 g ml^{-1} density sodium polystungstate (SPT) in a 250 mL centrifuge bottle. The mass of soil extracted was different for each sample but amounted to 2 mg soil organic carbon per sample, following Antony et al. (2022). Therefore, every tube contained the same ratio (2:80, w/v) of SOC to SPT (Table S1). The tubes were shaken for 30 seconds on an end-over-end shaker at 60 rpm and then centrifuged at 2500 *g* for 30 min. The supernatant containing the fPOM was immediately transferred after centrifugation into a 100 mL polypropylene bottle and filtered, using a Buchner vacuum filtration apparatus through a pre-weighed glass fibre filter (GF/A Whatman, UK) to obtain the fPOM. fPOM was then brushed off the GF paper and milled using mortar and pestle prior to fourier transform infrared (FTIR) spectroscopy analysis. fPOM was also analysed for carbon and nitrogen by dry combustion using a Thermo Flash 2000 C/N analyser, as described above for soil samples. Insufficient sample mass prevented the analysis of some samples.

2.2.3 | Fourier transform infrared spectroscopy analysis

Attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy analysis was undertaken on samples from selected soil layers (0–10 cm, 20–30 cm, 50–60 cm, and 90–100 cm) at each location and under each land use. Spectra were collected using a Perkin Elmer Spectrum 100 FTIR Spectrometer in the region from 4200 to 650 cm^{-1} recording 40 scans per sample at a resolution of 4 cm^{-1}.

Spectra observation identified 11 prominent peaks and shoulders that were present in most samples which indicate organic functional groups. Individual peaks were assigned to functional groups, as described in the Supporting Information and outlined in Table S2. To attribute differences in fPOM functional groups to SOM quality, a Decomposition Index was calculated using the relative absorbance of specific bands (Haberhauer et al., 1998; Margenot et al., 2015). To calculate the relative absorbance of each of the 11 bands used in the index, we divided the peak height of each peak (e.g., 3312, 2920, 2851, 2120, 1615, 1410, 1221, 1072, 931, 878, or 767 cm^{-1}) by the sum of the heights of all peaks at 3312, 2920, 2851, 2120, 1615, 1410, 1221, 1072, 931, 878, and 767 cm^{-1} and multiplied it by 100 (Haberhauer et al., 1998). The index was then calculated as a ratio of the relative absorbance of groups of bands representing aromatic and aliphatic functional group types following Equation 1 (Margenot et al., 2015).

$$\text{Decomposition Index} = \frac{1615 + 931 + 878 + 767}{2920 + 2851 + 1410} \quad (1)$$

The Decomposition Index is considered to indicate the degree of decomposition, as represented by the ratio of aromatic to aliphatic functional groups, because the ratios of bands representing these two functional groups have been shown to increase with increasing degree of decomposition (Hsu & Lo, 1999).

FTIR spectra were then standardized by z-scoring (mean centring and dividing by the standard deviation for each individual spectra) before statistical analysis (Hobley et al., 2017). The z-score for each of the 11 prominent peaks were taken forward to determine the impact of plantation age and soil depth on the prevalence of individual functional groups in fPOM.

2.3 | Statistical analysis

All statistical analyses were performed using Minitab v. 18. The Johnson transformation was carried out to get data normally distributed prior to running a mixed effects model. A mixed effects model was selected because it more robust to clustered data and unequal variances than analysis of variance. The analysis used land use and soil depth as fixed factors, whereas location was a random factor. Response variables were bulk density, SOC, nitrogen, C/N ratio, SOC stocks, FTIR z-scores, and Decomposition Index. The estimation method used was restricted maximum likelihood (REML) and the test method for fixed effects used the Kenward-Roger approximation, followed by a Tukey multiple comparison test ($p < .05$).

3 | RESULTS

3.1 | Soil physico-chemical properties

Conversion from natural forest to cinnamon plantation in Kerinci Regency, Sumatera, Indonesia, altered SOC concentrations in soils (Figure 2). The average SOC concentration down the soil profile of the natural forest ($54.5 \pm 10.2\,g\,kg^{-1}$) was significantly ($p < .05$) lower than the concentration in soils 1 year after conversion to cinnamon plantation ($68.61 \pm 6.22\,g\,kg^{-1}$), but then tended to be significantly ($p < .05$) lower in older plantations, particularly 10 year old plantations ($39.34 \pm 5.59\,g\,kg^{-1}$) (Table 1). Topsoils had significantly ($p < .05$) greater SOC concentrations than subsoils (Figure 2; Table S3).

Similar to SOC, nitrogen concentration revealed a comparable pattern whereby, compared with the natural forest ($3.71 \pm 0.71\,g\,kg^{-1}$), nitrogen was significantly ($p > .05$) greater in the 1-year-old plantation ($4.75 \pm 0.40\,g\,kg^{-1}$), but was lower in the 5 ($4.04 \pm 0.47\,g\,kg^{-1}$) and 10 ($3.02 \pm 0.37\,g\,kg^{-1}$) year old plantations (Figure 2; Table 1). When comparing the 1-year-old plantations with the 10-year-old plantations, average nitrogen concentrations were significantly ($p < .05$) lower in the 10-year-old plantations (Table 1). The top layer (0–10 cm) had significantly ($p < .05$) greater

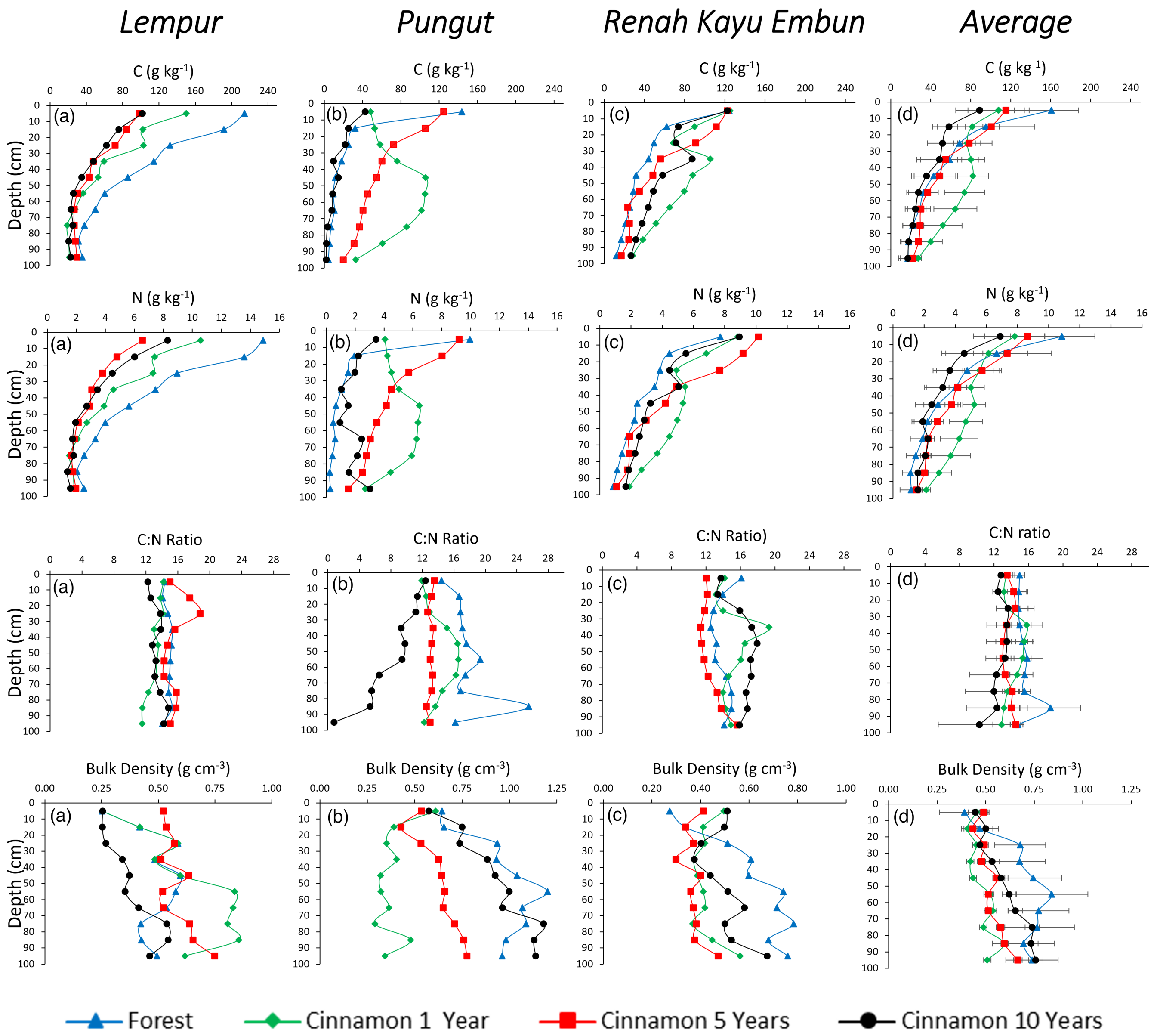

FIGURE 2 Soil Organic Carbon ($g\,kg^{-1}$), nitrogen ($g\,kg^{-1}$), C/N ratio, and bulk density ($g\,cm^{-3}$) at 10 cm depth increments to 1 m under forest and several different ages of Cinnamon plantation (1, 5, and 10 years old, respectively) at Lempur (a), Pungut (b), and Renah Kayu Embun (c) locations in Kerinci, Jambi Province, Indonesia. Graph (d) of each parameter shows the mean values from all three locations and error bars represent the standard errors of the mean using the three locations as replicates.

Land use	Bulk density ($g\,cm^{-3}$)	Carbon ($g\,kg^{-1}$)	Nitrogen ($g\,kg^{-1}$)	C/N ratio
Forest	0.68 ± 0.05 a	54.50 ± 10.2 bc	3.71 ± 0.71 b	15.54 ± 0.45 a
Cinnamon Y1	0.48 ± 0.03 b	68.61 ± 6.22 a	4.75 ± 0.40 a	14.13 ± 0.32 ab
Cinnamon Y5	0.53 ± 0.03 ab	54.36 ± 5.95 ab	4.04 ± 0.47 ab	13.78 ± 0.32 b
Cinnamon Y10	0.60 ± 0.05 ab	39.34 ± 5.59 c	3.02 ± 0.37 b	12.61 ± 0.74 b

Note: Different letters within a column represent statistically significant differences at $\alpha = .05$.

TABLE 1 Soil properties in the top 1 m of the soil profile under natural forest and 1-, 5-, and 10-year-old cinnamon plantations from three locations in the Kerinci Regency, Jambi Province of Indonesia (mean ± standard error mean, $n = 30$).

concentrations of nitrogen than deeper (20–100 cm) layers (Table S3).

The C/N ratio of the soils was significantly ($p < .05$) lower with time after conversion to cinnamon plantation (Figure 2). The C/N ratio of the forest soils (15.54 ± 0.45) was significantly greater ($p < .05$) than the soils from 5-year-old (13.78 ± 0.32) and 10-year-old (12.61 ± 0.74) cinnamon plantations but were not significantly different ($p > .05$) to the 1-year-old (14.13 ± 0.32) plantations (Table 1). However, there were no significant differences in C/N ratio between any layers down the soil profile (Table S3).

All soils had a low bulk density which was consistently under 1.0 $g\,cm^{-3}$, ranging from 0.48 to 0.68 $g\,cm^{-3}$ (Figure 2) and increasing down the soil profile, with statistically significant ($p < .05$) differences observed, particularly between the top and bottom layers (Table S3). Statistical analysis indicated that forest soil (0.68 ± 0.05 $g\,cm^{-3}$) had a significantly ($p < .05$) greater bulk density than 1–year-old cinnamon plantation (0.48 ± 0.03 $g\,cm^{-3}$), while no significant ($p > .05$) differences were observed between the bulk density of 10-year-old (0.60 ± 0.05 $g\,cm^{-3}$) and 5-year-old (0.53 ± 0.03 $g\,cm^{-3}$) cinnamon plantations (Table 1).

3.2 | Soil carbon stocks

On average, carbon stocks of the 10 cm layers decreased significantly ($p < .05$) down the soil profile (Table S3). Carbon stocks to 1 m soil depth (Figure 3) were greatest under 1-year-old cinnamon plantations (294.83 ± 21.94 Mg Ha^{-1}), significantly ($p < .05$) greater than those observed under 10-year-old cinnamon plantations (180.85 ± 22.01 Mg Ha^{-1}), but not significantly ($p > .05$) different to the forest soils (278.05 ± 42.06 Mg Ha^{-1}), or the 5-year-old cinnamon plantations (275.43 ± 27.13 Mg Ha^{-1}) (Table 2).

The impact of soil depth and land use on carbon stocks was further investigated by calculating stocks based on topsoil (0–30 cm) and subsoil (30–100 cm) layers (Figure 3). Forest soils (143.0 ± 37.9 Mg Ha^{-1}) had the greatest topsoil carbon stocks, which were significantly ($p < .05$) greater than the 10-year-old cinnamon plantations (83.1 ± 22.5 Mg Ha^{-1}), but not significantly different ($p > .05$) to either the 5-year-old (136.6 ± 8.25 Mg Ha^{-1}) or 1-year-old (113.0 ± 21.6 Mg Ha^{-1}) cinnamon plantations (Table 2). Interestingly, 1-year-old cinnamon plantations had the largest subsoil carbon stocks (181.8 ± 12.1 Mg Ha^{-1}), and these were significantly ($p < .05$) greater than the forest subsoil carbon stocks (135.0 ± 42.9 Mg Ha^{-1}) and 10-year-old cinnamon plantation subsoil carbon stocks (97.7 ± 33.7 Mg Ha^{-1}), but not significantly ($p > .05$) different to 5-year-old cinnamon plantation subsoil carbon stocks (138.8 ± 31.7 Mg Ha^{-1}) (Table 2).

3.3 | Free particulate organic matter (fPOM)

The carbon and nitrogen concentration and C/N ratio of the fPOM fraction were not significantly different ($p > .05$) between the natural forest and cinnamon plantations of different ages (Table S4, Figure 4). However, we did observe differences in carbon and nitrogen concentration and C/N ratio of fPOM down the soil profile, between topsoils and subsoils (Table S5, Figure 4). Carbon and nitrogen concentrations of fPOM were greater in topsoils and were significantly ($p < .05$) lower in subsoils, whereas fPOM C/N ratio was lower in topsoils and tended to increase with depth (Table S5, Figure 4).

The raw FTIR-ATR spectra of the fPOM fraction (Figure S1) revealed several characteristic major absorbance peaks representing the molecular structure of fPOM in the frequency range of 4000–600 cm^{-1}. Although the influence of soil depth and land use on the z-score transformed absorbance of all 11 identified peaks observed in the FTIR spectra of fPOM were analysed using the mixed effects model (Table S6), only bands attributed to aromatic C-H (bands 767, 878, and 931) and O functional groups (band 3312) and carbohydrate (2120) significantly ($p < .05$) differed with land use (Table 3). All these bands showed a similar pattern with absorbance intensity in the order Forest >Cinnamon Year 1 >Cinnamon Year 10 >Cinnamon Year 5, except band 3312 (attributed to O functional groups), which showed the opposite pattern (i.e., Forest <Cinnamon Year 1 <Cinnamon Year 10 <Cinnamon Year 5). The intensity of z-score transformed absorbance of aromatic C-H (bands 767 and 878)

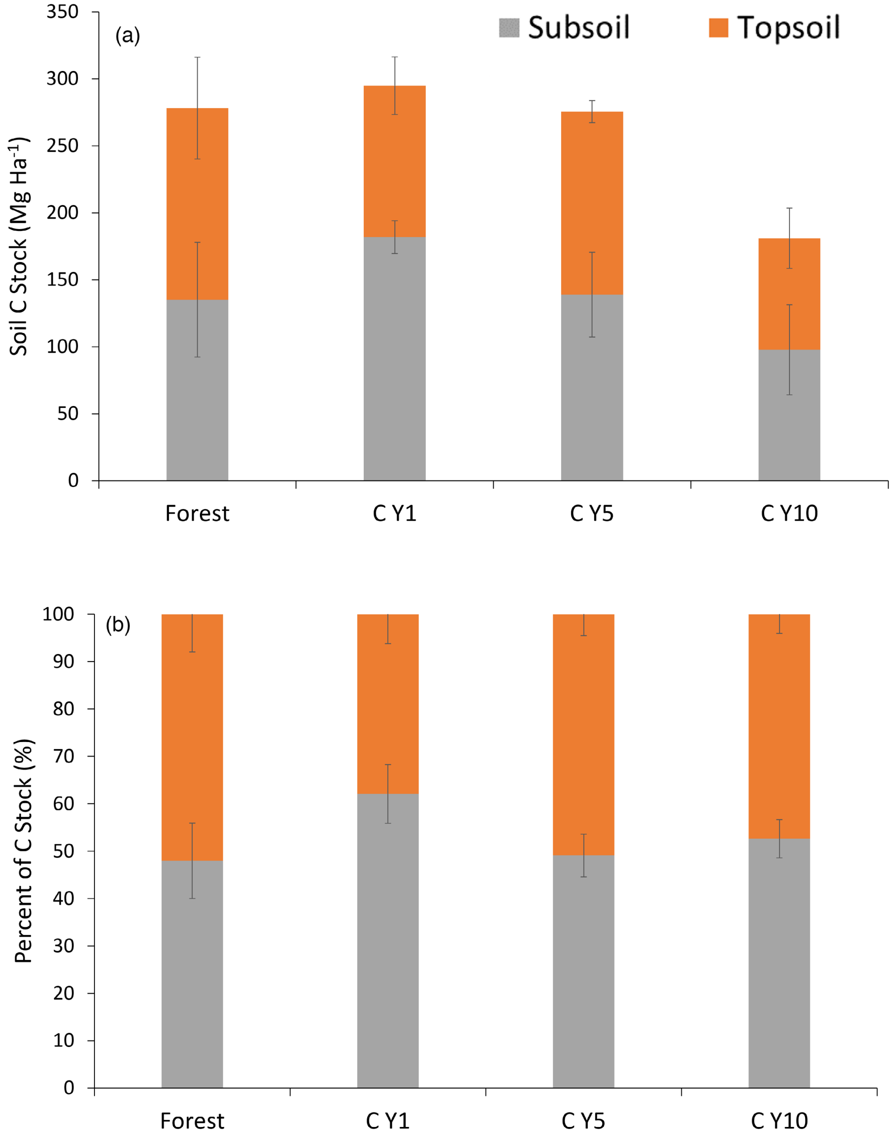

FIGURE 3 Mean Soil Organic Carbon (SOC) stocks in topsoil (0–30 cm) and subsoil (30–100 cm) layers expressed in Mg Ha^{-1} (a) and as a percentage of whole profile stock (b) under natural forest and three different ages of cinnamon plantation (i.e., at year 1 (C Y1), year 5 (C Y5) and year 10 (C Y10) after conversion from natural forest) from three locations in the Kerinci Regency, Jambi Province of Indonesia.

TABLE 2 SOC stocks (Mg Ha^{-1}) (mean ± standard error mean, $n = 3$) under different land uses and layers; topsoil (0–30 cm), subsoil (30–100 cm), and whole profile (0–100 cm).

	SOC stocks (Mg ha^{-1})		
Land use	**Topsoil**	**Subsoil**	**Profile**
Forest	143.0 ± 37.9 ab	135.0 ± 42.9 b	278.0 ± 74.1 a
Cinnamon Y1	113.0 ± 21.6 ab	181.8 ± 12.1 a	294.8 ± 12.2 a
Cinnamon Y5	136.6 ± 8.25 a	138.8 ± 31.7 ab	275.4 ± 39.9 a
Cinnamon Y10	83.1 ± 22.5 b	97.7 ± 33.7 b	180.8 ± 55.6 b

Note: Different letters within a column represent statistically significant differences at $\alpha = .05$.

decreased significantly ($p < .05$) with depth (Table 4), indicating that the aromaticity of fPOM in topsoil was significantly ($p < .05$) greater than the subsoil fPOM.

The Decomposition Index (Figure 4d), which represents the abundance of aromatic C=C and C-H functional groups, relative to aliphatic C-H functional groups, was significantly ($p < .05$) affected by land use, but not soil depth ($p > .05$). We observed that the Decomposition Index ordered the land uses in the following order: Forest >Cinnamon Year 10 >Cinnamon Year 1 >Cinnamon Year 5 (Figure 4d). fPOM from the Forest soils had a significantly ($p < .05$) higher fPOM Decomposition Index value than the 5-year-old cinnamon plantation soils but was not significantly different ($p > .05$) to 1–year-old or 10–year-old cinnamon plantations (Table 3). This trend indicates that the degree to which fPOM was decomposed decreased after forest conversion until 5 years after cinnamon plantation, but then increased again after 10 years.

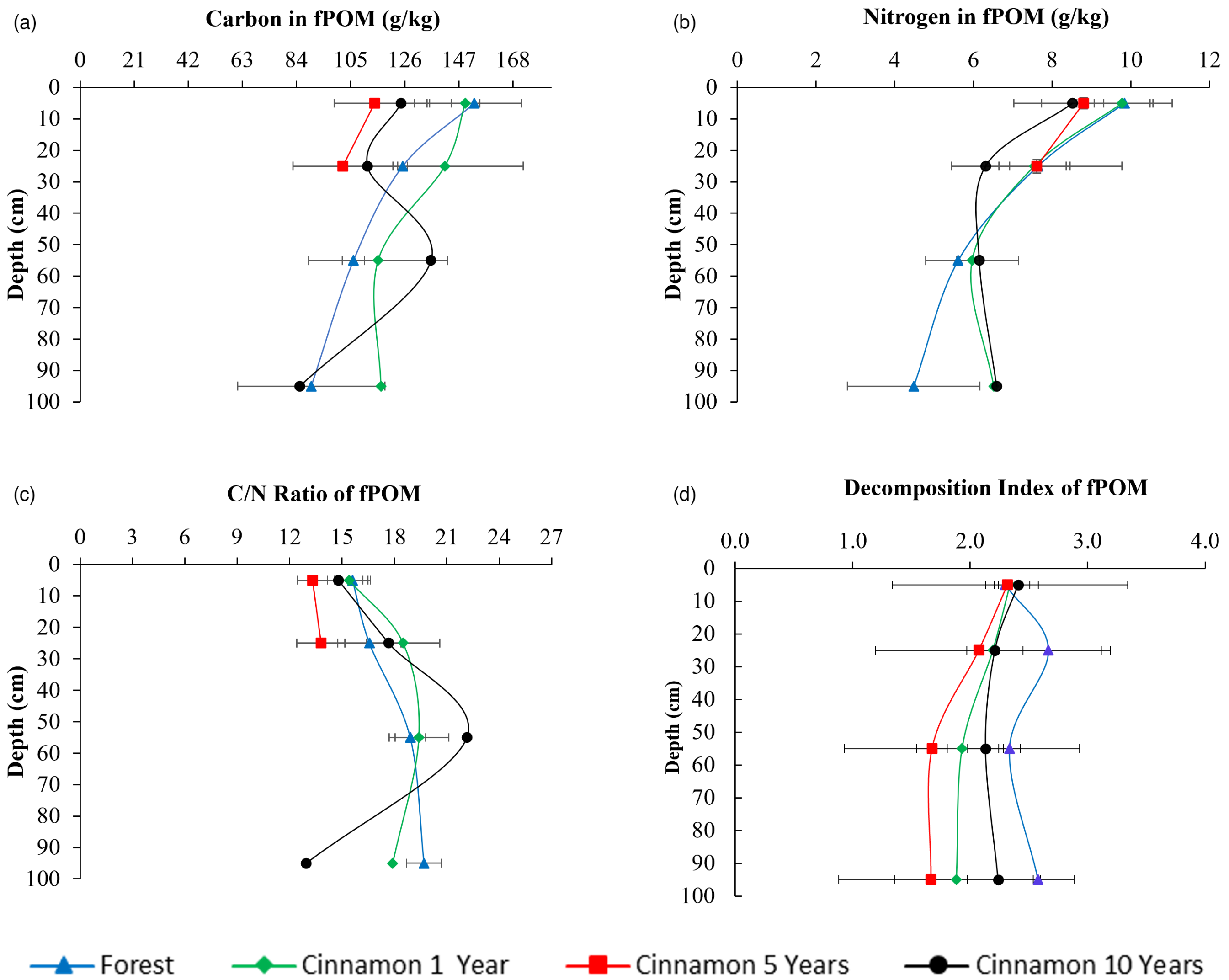

FIGURE 4 Concentration of carbon (a), nitrogen (b), C/N ratio (c), and the fourier-transform infrared (FTIR) spectroscopy derived Decomposition Index (d) of free particulate organic matter (fPOM) down the soil profile under forest and several different ages of Cinnamon plantation (1, 5, and 10 years old, respectively) from three locations in the Kerinci Regency, Jambi Province of Indonesia (mean ± standard error mean, $n=3$). Insufficient fPOM was obtained for carbon and nitrogen analysis in the 5-year-old cinnamon plantation subsoils.

4 | DISCUSSION

4.1 | Topsoil and subsoil carbon stocks in tropical Andosols

The soils present at all three villages in Kerinci Regency, Sumatera, Indonesia, where samples were taken for this project, are classified as Andosols, as evidenced by the soil map (Figure 1). Andosols are soils that are derived from volcanic materials, are rich in organic matter, have high porosity, and usually have a low bulk density (McDaniel et al., 2012; Takahashi & Shoji, 2002). Despite andosols, or volcanic ash soils, representing just 0.84% of land globally, they contain approximately 5% of global soil carbon (Eswaran et al., 1993). Andosols contain allophane and imogolite minerals, which, besides Al and Fe oxides, are amongst the most effective minerals to bind SOC, thus making andosols the most carbon-rich mineral soil type (Zieger et al., 2018).

The size of the SOC stock that we measured in the top 1 m of soil under the natural rainforest in the Kerinci Regency of Jambi Province in Indonesia (278 Mg Ha^{-1}) was slightly smaller than global average andosol SOC stock (290 Mg Ha^{-1}) reported by Batjes (1996) and considerably lower than andosol SOC stocks measured in tropical rain forests in Hawaii (375 Mg Ha^{-1}) by Marin-Spiotta et al. (2011), in the Amazon basin (301 Mg Ha^{-1}) by Zieger et al. (2018), and in Ecuadorian forests (530 Mg Ha^{-1}) by Tonneijck et al. (2010). In agreement with our observations, about 50% of total C stocks in rainforest soils are observed by Marin-Spiotta et al. (2011) to be stored in subsoil layers. However, global soil data found

TABLE 3 Relative absorbance (z-score transformed absorbance) of selected bands obtained from Fourier-transform infrared (FTIR) spectra of free particulate organic matter (fPOM) in topsoil and subsoil under forest and several different ages of Cinnamon plantation (1, 5, and 10 years old, respectively) from three locations in the Kerinci Regency, Jambi Province of Indonesia (mean ± standard error mean, $n = 12$).

	Land use			
Band (cm^{-1})/index	Forest	Cinnamon Y1	Cinnamon Y5	Cinnamon Y10
767	2.79 ± 0.26 a	2.76 ± 0.47 a	1.65 ± 0.42 b	2.03 ± 0.19 ab
878	2.98 ± 0.12 a	2.38 ± 0.32 ab	1.56 ± 0.29 c	2.25 ± 0.12 b
931	1.81 ± 0.08 a	1.65 ± 0.13 ab	1.22 ± 0.22 b	1.42 ± 0.09 ab
2120	−0.55 ± 0.03 ab	−0.59 ± 0.03 ab	−0.48 ± 0.08 a	−0.68 ± 0.01 b
3312	1.05 ± 0.15 b	1.60 ± 0.10 a	1.80 ± 0.19 a	1.61 ± 0.06 a
Index	1.78 ± 0.08 a	1.50 ± 0.06 ab	1.41 ± 0.08 b	1.66 ± 0.08 ab

Note: Different letters within a column represent statistically significant differences at $\alpha = .05$.

TABLE 4 Relative absorbance (z-score transformed absorbance) of selected bands obtained from Fourier-transform infrared (FTIR) spectra of free particulate organic matter (fPOM) from selected soil layers of the soil profile under natural forest and three different ages of cinnamon plantation (1, 5, and 10 years old, respectively) from three locations in the Kerinci Regency, Jambi Province of Indonesia (mean ± standard error mean, $n = 12$).

	Bands	
Soil layer	767	878
0–10 cm	3.03 ± 0.35 a	2.70 ± 0.20 a
20–30 cm	2.52 ± 0.31 ab	2.44 ± 0.22 ab
50–60 cm	1.81 ± 0.41 b	2.01 ± 0.33 b
90–100 cm	1.86 ± 0.33 b	2.01 ± 0.28 b

Note: Different letters within a column represent statistically significant differences at $\alpha = .05$.

that subsoils typically contain around 55% of SOC stocks (Batjes, 1996).

4.2 | Effect of land use change on soil organic matter and carbon stocks

The low soil bulk density (0.48–0.68 g cm^{-3}) that we observed at all our study sites in Kerinci Regency, Sumatera, Indonesia, is similar to observations made on other Indonesian andosols (0.37–0.9 g cm^{-3}) by Sukarman (2014) and are within the range of global data (0.28–0.99 g cm^{-3}) reported by Batjes (1996). Moreover, we observed a significant decrease in soil bulk density in the first year after conversion from forest vegetation (0.68 g cm^{-3}) to cinnamon plantation (0.48 g cm^{-3}). During the first year of conversion from forest to cinnamon farmers usually intercrop cinnamon trees with annual crops such as chilli and upland rice (Hariyadi & Ticktin, 2012). The significant decrease in bulk density after forest conversion to cinnamon plantation is probably partly because of an increase in pyrogenic soil organic matter (Thomaz, 2017; Thomaz et al., 2014) owing to the burning of aboveground vegetation (Filho et al., 2015). Pyrogenic material has a lower density than mineral soil or fresh organic matter, entering the soil because of the slashing and burning of vegetation prior to cultivation (McDaniel et al., 2012). Studies on the impact of fire associated with shifting cultivation (Ando et al., 2014; Tanaka et al., 2001) found that burning increases SOC and soil nitrogen concentrations, which we did observe (Figure 2 and Table 1). However, the cleared land is only fertile for a couple of years before the nutrients released by slash and burn are exhausted (Sukarman, 2014).

After an initial increase following conversion from natural forest to cinnamon plantation, we observed decreasing SOC stocks along a chronosequence of cinnamon plantations with increasing age. Our observations are specific to the sites we visited in Kerinci Regency, Sumatera, Indonesia, and should not be extrapolated beyond this region. However, our finding that land use change ultimately reduces soil SOC stocks in the long term (Figure 3) is in accordance with several studies on carbon stocks that report SOC losses after land uses conversion from primary forest to agricultural land (Don et al., 2011; Filho et al., 2013; Lal, 2018; van Straaten et al., 2015). The decrease in bulk density observed after conversion from forest to cinnamon plantation not only directly influences the calculation of SOC stocks. It also causes the soil to become more porous, resulting in more SOM to be transported by leaching to the subsoil, leading to an increase in the SOC and nitrogen concentration (Figure 2) and carbon stock (Figure 3) in the subsoil. This leaching was also noted in a review of shifting cultivation systems by Ribeiro Filho et al. (2013). Supporting this interpretation is the observed increase in the proportion of the SOC stock that is stored in the subsoil layer of the soils converted from forest to cinnamon plantations of all ages. Zieger et al. (2018) revealed that larger SOC stocks in the subsoils than the topsoils of andosols, despite high SOC inputs, were because of the limited binding capacities of topsoil mineral phases. Therefore, the less strongly bound SOM entering topsoils moves through the soil profile to deeper layers of the soil because of leaching processes (Kaiser & Kalbitz, 2012) and is most likely largely leached out of the top 1 m within 5 years of conversion. This interpretation is supported by the declining abundance of carbohydrate groups in the fPOM (Table 3) in the older cinnamon plantations, indicating a lower input of fresh material (Hsu & Lo, 1999). The lower C/N ratio and increasing abundance of hydroxyl groups indicate faster decomposition leading to SOC loss (Hsu & Lo, 1999; Veum et al., 2014; Yeasmin et al., 2020). Loss of SOC, particularly fPOM, after land use change from natural vegetation to cultivation is well established in the literature, and usually occurs within a few years of starting cultivation (Ashagrie et al., 2007; Murty et al., 2002).

4.3 | Effect of land use change on soil organic matter quality at depth

While we observed no effect of soil depth on soil C/N ratio, we did observe that C/N ratio was significantly lower 10 years after conversion to cinnamon plantation, largely because carbon decreases to a greater extent than nitrogen. The decrease in soil C/N ratios after conversion may reflect enhanced microbial processing of soils and/or improved quality of organic matter input (van Straaten et al., 2015). We investigated this further by obtaining the fPOM fraction of the SOM since this is the fraction that is most easily accessible by soil organisms and thus drives many soil functions (Hoffland et al., 2020; Lavallee et al., 2019).

In accordance with the study of Guo et al. (2010), we found that fPOM of different land uses have similar FTIR spectra (Figure S1). Further investigation to the fPOM fractions indicated that carbon content of fPOM decreases down the soil profile and there was a lower abundance of aromatic C-H groups and a higher C/N ratio of the fPOM down the soil profile. This observation could imply that there is less fresh plant material (e.g., carbohydrates and lignin) in the subsoil, implying that particulate organic matter in the subsoil is less microbially processed (Veum et al., 2014). Greater C/N ratio in subsoils than topsoils also indicates different sources of fPOM, with subsoils mainly receiving carbon from fine roots (Soucémarianadin et al., 2019) with a higher C/N ratio (Hobbie et al., 2010) compared with fresh foliage in topsoils which have a lower C/N ratio (Cools et al., 2014).

We observed that the degree of decomposition (Decomposition Index) of the fPOM fraction of SOM was greatest in the forest soils and that this tends to decrease after conversion to cinnamon plantation, but again increases 10 years after conversion (Figure 4). The abundance of aromatic groups (bands 767, 878, 931) in forest soils was greater than soils after conversion, indicating more decomposed organic matter (Veum et al., 2014). This also arises because of more litter input from vegetation to soil, which leads to higher decomposition rates by microorganisms (Jobbágy & Jackson, 2000). The total SOC stock of the 10-year-old cinnamon plantation was the lowest of all the land uses surveyed and the degree of decomposition of the fPOM was higher than the more recently converted plantations, which demonstrates the progression of decay of the flush of fresh organic inputs that resulted from the slash and burn activities (Margenot et al., 2015). Further observation of fPOM quality at depth revealed a decreasing content of aromatic-C with depth indicating less microbial activity in subsoils, supported by the study of Soucémarianadin et al. (2019) which revealed that fPOM chemistry variations depend on vegetation and soil depth.

5 | CONCLUSION

In the first year after conversion from natural forest to cinnamon plantation SOC stocks in soils sampled in Kerinci Regency, Sumatera, Indonesia, increased and the degree of decomposition of the fPOM decreased owing to slash and burn activities adding fresh organic matter into the soil profile. The addition of pyrogenic carbon into the soil during slash and burn decreases bulk density which directly influences the calculation of soil carbon stocks and facilitates the leaching of organic matter down the soil profile where it increases subsoil SOC stocks in the short term. However, in older cinnamon plantations an increase in the degree of decomposition of the fPOM fraction is observed and the lack of fresh litter input results in a lower SOC stock in both topsoils and subsoils. While conversion of forest to cinnamon plantation decreased SOC stocks, additional analyses (e.g., pH, microbial activity, and soil structure) would be required to quantify the impact of this land use change on overall soil health.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Mendeley Data at https://data.mendeley.com, reference number 10.17632/6t87xwfwph.1

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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