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Impact of Rubber Tree Plantations Chronosequence on Soil Fertility and Soil Organic Carbon stocks, Gurafarda District, Southwest Ethiopia

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Abstract

Rubber tree is one of the important commercial commodities in the globe. This study was conducted to examine the change in soil fertility and soil organic carbon stocks following conversion of forest to rubber plantation of different ages (5, 10, 15, 20 and 25 years) and coffee agroforestry. The field experiment was conducted in Guraferda district, Southwest Ethiopia. The soil samples were collected from 20× 20 m ^{2} plots at 30 cm depth, with three replicates at a 100 m interval. A total of 42 soil samples were taken from the three land-use types. The soil moisture content (MC), porosity, soil pH, organic carbon (OC), total nitrogen (N), available phosphorous (P), exchangeable bases, CEC (cation exchange capacity) and base saturation (B)S content of the NF (natural forest), CA(coffee agroforestry) and old age rubber plantation (RP15, RP20 and RP25) were higher than the early years of rubber plantation (RP5 and RP10). The highest soil organic carbon stocks (SOC) were recorded in NF (114.3 Mg ha $^{-1}$), CA (112.2 Mg ha $^{-1}$), RP25 (98.5 Mg ha $^{-1}$) and RP20 (97.8 Mg ha $^{-1}$). The SOC loss because of conversion of NF to RP5 (11.0 Mg ha $^{-1}$ y $^{-1}$), RP10 (5.3 Mg ha $^{-1}$ y $^{-1}$), RP15 (2.3 Mg ha $^{-1}$ y $^{-1}$), RP20 (0.8 Mg ha $^{-1}$ y $^{-1}$), RP25 (0.6 Mg ha $^{-1}$ y $^{-1}$) and CA (0.1 Mg ha $^{-1}$ y $^{-1}$). In general, old age rubber plantation (RP20 and RP25) showed proportional levels of soil fertility and soil organic carbon stocks compared with the natural forest and the coffee agroforestry. Since all physico-chemical characteristics were low at the early years of rubber plantation, we recommend to supplement significant proportions of nutrient to the early years of rubber plantation (0-10 years).

Keywords: *Rubber plantation, Land use types,* Physico-chemical characteristics, Soil organic carbon stocks, Organic carbon loss.

INTRODUCTION

Background

Rubber (*Hevea brasiliensis* Muell. Arg.) is indigenous to South America and belongs to the Euphorbiaceae family (Torres et al., 2020). The plant expanded to many tropical countries in South Asia, Southeast Asia, and in tropical West Africa. Today, Southeast Asia is the leading producer of natural rubber (FAO, 2013) which roughly contributes 97% of the world's natural rubber (Li and Fox, 2012). Globally, land under rubber has expanded from 8.8 million hectare in 2000 to 12.9 million hectares in 2016 (FERN, 2018). In 2020, the total rubber tree covers reaches 14.1 million hectares (IRSG, 2020). This expansion was largely at the expense of tropical natural forest (Cheng, 2007; Laumonier et al., 2010; Warren-Thomas et al., 2015; Chambon et al., 2016).

Rubber tree plantations are the principal commercial sources of natural rubber, a valuable raw material for several rubber-based industries in different parts of the world (Vaysse et al., 2012). In addition to being one of the major cash crops produced in many tropical countries in South America, Asia, and Africa (Vaysse et al., 2012; Huang et al., 2020), the cultivation of rubber tree can be used for restocking deforested and degraded areas (Torres et al., 2020). Further, tree canopy and litter plays an important role in reducing soil erosion, increase the soil water holding capacity and nutrients cycling (Kassa et al., 2017). Besides, rubber tree cultivation can store a considerable amount of carbon in biomass and soil (Diniz et al., 2015). However, the conversion of natural forests to rubber plantations have led to decline in soil organic carbon stocks (Don et al., 2011; de Blécourt et al. 2013) and above ground biomass carbon stocks (de Blécourt et al. 2013; Yang et al., 2016), soil fertility (Liu et al., 2019), loss of biodiversity (Warren-Thomas et al., 2015; Cotter et al., 2017; Hughes, 2017), decline in ecosystem services (Ziegler et al., 2009; Tan et al., 2011), increases in greenhouse gas emissions (Zhou et al. 2016) and soil erosion (Guillaume et al. 2015; Liu et al., 2017). Furthermore, Chun-man et al. (2007) and Ekukinam et al. (2014) reported a decline in soil fertility with an increase in stand age of rubber tree.

In Ethiopia, rubber tree (*Hevea brasiliensis*) has been cultivated in the forest zone, mainly in the warm and humid southwest since 1990s and currently rubber plantation has been expanding at the expense of natural forest. In the southwest Ethiopia, the land under rubber plantation is 10,465 ha with over 84000 ha of additional land set aside for future development in southwest Ethiopia (EIA, 2012; GDANRO, 2015). However, southwest natural forests are important for climate and soil quality regulation (Mekuria, 2005; Kassa et al., 2017). For example, the soil under natural forest in southwest Ethiopia can holds up to 8.2%, 1.1%, 14 mg kg^{-1}, 94 cmol kg^{-1} organic carbon (OC), nitrogen (N), P (phosphorus), and CEC respectively in the top soil (0-20 cm); and stores 153 Mg ha^{-1} of soil organic carbon (Kassa et al., 2017).

Conversion of natural forests to agriculture and cultivation of commercial tree plantation have led to soil fertility and soil organic carbon decline (Lemenih, 2004). For example, Mekuria (2005) reported a decline of 12% in OC, 8% in N, 72% in P, 58% in K, 14% in base saturation following 57 years subsequent cereal crop cultivation after conversion of forest in Ethiopia. Cheng et al. (2007) and Guillaume et al. (2016) reported a decrease in soil fertility and soil organic carbon stocks with the increase in cultivation age of rubber plantation in China and Indonesia. On the contrary, Saengruksawong et al. (2012) reported an increase in soil fertility and soil organic carbon stocks with the increase in cultivation age of rubber plantations in Thiland.

Furthermore, the rate and magnitude of decline in soil fertility and soil organic carbon depends on additional factors like climate, topography, plant variety, soil microbes, land use intensity and soil type etc (Tiessen et al., 1994; Tinker et al., 1994).

Therefore, a regional scale evaluation of soil quality and soil organic carbon stocks following conversion from forest and subsequent cultivation is very important to provide practical guidance to design local level solution, strategic, policy and for sustainable land management practice.

Objectives

General objective

- ✓ To examine the change in soil fertility and soil organic carbon stocks following the conversion of forests to rubber plantations of different ages (5, 10, 15, 20 and 25 years) and coffee agroforestry.

Specific objective

- ✓ To estimate change in soil organic carbon stocks and carbon dioxide loss following the conversion of forest to rubber tree plantations of different ages.

Methodology/approach

Description of the study Area

The study was conducted in Guraferda district, Southwest Ethiopia. The study area is located 603 km south west of Addis Ababa, the capital city of Ethiopia. It lies between 6°29’5”- 7°13’20” N and 34°55’59”- 35°26’13” E **(**Figure 1**)** and covers an area of 2565.4 km^2. The study area elevation ranges from 700 m to 2300 m. Climate is composed of warm and humid, with average annual rainfall of 1639 mm and temperature of 24°C (Belay, 2018). The dominant soil types are Nitosols, Acrisols, and Cambisols (Dewitte et al., 2013) and the geology is dominated by volcanic materials of the tertiary period (Mohr, 1971).

The natural vegetation of the area is largely dominated by moist evergreen montane forest. According to Edward (2010), the characteristic species in this vegetation includes *Pouteria adolfi-friedericii, Olea capensis, Prunus africana, Albizia schimperiana,Cordia africana*, *Mimosops kummel*. The coffee agroforestry land of Guraferda district is composed of *Coffea arabica*, as main cash crop integrated with fruits (mango, avocado and papaya), spices (Black pepper), shade trees (*Millettia ferruginea* and *Grevillea robusta*). Rubber trees are plantations composed of rubber tree planted as monoculture and the rubber plantation composed of plantation blocks of different ages (5, 10, 15, 20, and 25 years) in the same altitudinal belts.

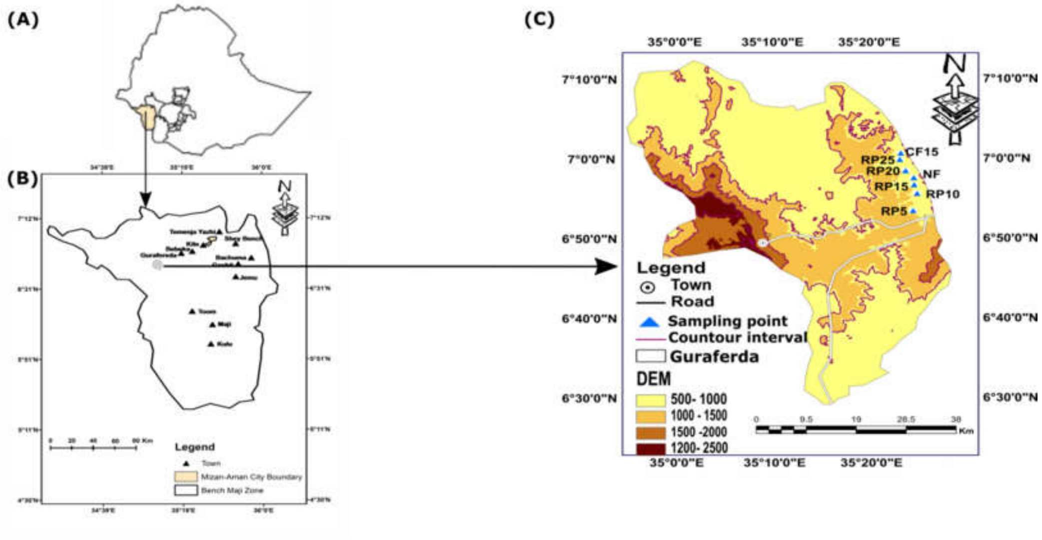

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Fig. 1: Map of the study area. Soil sampling plots. (A) location of study sites in Ethiopia; (B) Study site in Bench Sheko Zone; (C) location of study sites with sampling point, Southwest Ethiopia.

Methods

Soil sampling

The soil samples were taken in April and May 2019. Preliminary survey and field observation were carried out to generate key information such as, topography, land uses, vegetation cover and locating representative soil sampling points. Accordingly, three major representative land use types (natural forest, 15 years old coffee agroforestry and five different aged rubber tree plantations: 5, 10, 15, 20, and 25 years old in 2019), which are adjacent to each other and same altitudinal belt (1200 m a.s.l) were selected in this study. Soil samples were collected using a soil auger from 0-30 cm soil depth which is believed to constitutes the average depth to which trees litter, nutrient and clay particles are leached (Kassa et al., 2017). The land use history of the soil sampling points were collected from the district agriculture and natural resources office and investment office.

The soil samples were collected from 400 m^2 plots with three replicates at a 100 m interval. A total of 42 soil samples were taken from the three land-use types. Separate soil samples were gathered at the middle of each plot for soil bulk density determination. About one kilogram of composite soil samples were packed using plastic bags and sent to Addis Ababa National Soil Testing Center and Oromia Engineering cooperation laboratory for physico-chemical analysis.

Physico-chemical analysis

The bulk density (BD) of the soil was measured from undisturbed soil samples collected using 100 cm^3 *Kopecky rings, the total porosity of soil samples was estimated from the values of bulk density (BD) and particle density (PD)* *(assuming an average particle density of mineral soil is 2.65 g cm^{-3}). Then the total porosity (TP) was calculated according to Danielson et al. (1986) as,*

TP (%) = (1-Bulk density/Particle density) x (100)………………………………………… (1)

The pH of the soils was measured in water (H_2O) suspension in a 1:2.5 (soil: water) by pH meter. The total nitrogen content in soils was determined using the Kjeldahl method (Bremner and Mulvaney, 1982), organic carbon contents (Walkley and Black, 1934), organic matter content of the soil was calculated by multiplying the value of organic carbon with the Van Bemmelen factor, 1.724 (Piper, 1950). The available phosphorus was determined by Olsen method (Olsen et al., 1954), exchangeable bases (Na, K, Mg and Ca) were determined after extracting the soil samples by ammonium acetate (1N NH4OAc) at pH 7.0. Exchangeable Na and K were analyzed by flame photometer while Ca and Mg in the extracts were analyzed using atomic absorption spectrophotometer (AAS) as described by Rowell (1994). Cation exchange capacity was determined by the ammonium acetate method (Hesse, 1972). Percent base saturation was calculated by using standard formula:

BS= $[(Na^{+}+K^{+}+Ca^{2+}+Mg^{2+})/CEC]$ x 100…………………………………………………… (2)

The soil organic carbon stocks was calculated based the following formula (Chan, 2008).

Ct: Kd x ρ x %C…………………………………………………………………………….. (3)

Where Ct=Carbon stock (Mg C ha^{-1}), Kd=the thickness of the sampled soil layer (cm), ρ= bulk density (g/cm^3), %C= the percentage of soil organic carbon.

The losses in soil organic carbon due to deforestation were estimated by subtracting the total soil organic carbon stocks under forest from that of the corresponding depth under coffee agroforestry and different years of rubber plantation. The computed loss values were then divided by the number of years since the conversion to obtain soil organic carbon losses per year. The carbon dioxide emission due to the conversion of forest to rubber plantation was calculated based on the ratio of the molecular weight of carbon dioxide to that of carbon (44/12=3.67 reported by Chan et al. (2008); thus, increase in 1 Mg ha^{1} in soil carbon represents a 3.67 Mg ha^{-1} of carbon dioxide removal from the atmosphere.

Statistical analysis

Statistical significance of topsoil physico-chemical characteristics of the natural forest, coffee agroforestry, and rubber plantations of five different ages were assessed using one-way ANOVA using IBM SPSS Statistics v.22. Mean differences between treatments were compared by least significant difference (LSD) at $p < 0.05$.

Results

Soil physical characteristics

Soil bulk density

The soil bulk density of the early years rubber plantation was significantly different from forest and coffee agroforestry land uses types ($p<0.05$) (Table 1). The soil bulk density was the highest in 5-year-old rubber plantation (RB5) (1.38±0.07 g cm^{-1}) followed by 10-year-old rubber plantation (RB10). However, no difference was found in soil bulk density between RB15, RB20 and RB30 with both forest and agroforestry land use types (Table 1).

Soil moisture content

There is significance difference ($p<0.01$) in soil moisture content between forest land use and early years of rubber plantation (RP5 and RP10), old age of rubber plantation and coffee agroforestry land use types. However, no difference in soil moisture content was found between coffee agroforestry and old years of rubber plantation (RP15, RP20 and RP25). The highest soil moisture content was recorded in natural forests (37.1±4.7%), followed by coffee agroforestry (34.8±3.1%) and RP25 (30.6±3.7%) (Table 1). The study revealed that soil moisture content substantially increased with increasing age of rubber plantation in the study area (Table 1).

Porosity

The soil porosity of the forest is significantly different ($p\leq0.05$) from early years of rubber plantation sites, however similar with coffee agroforestry and old aged rubber plantation sites. The highest soil porosity was recorded in NF (55.3%) and CA (55.3%), followed by RP25, RP20 and RP15 (Table 1). The presence of higher soil porosity in those land use types and old aged rubber plantation could be associated with the presence of high organic carbon content on those sites.

Table 1: Soil physical characteristics of the land use types and different age categories of rubber plantation

Land use types and rubber plantation chronosequence	Physical characteristics		
	BD (g cm^{-3})	MC (%)	PO (%)
RP5	1.38±0.07a	21.9±3.5c	44.9±2.5b
RP10	1.3±0.15a	21.2±4.4c	45.0±5.3b
RP15	0.83±0.15b	30.4±2.8b	50.7±3.8a
RP20	0.89±0.14b	30.1±4.3b	54.0±1.0a
RP25	0.87±0.1b	30.6±3.7ab	55.0±2.6a
CA	0.88±0.15b	34.8±3.1ab	55.3±2.5a
NF	0.87±0.15b	37.1±4.7a	55.3±3.0a
Overall mean ±SD	1.0±0.24	29.4±6.5	51.5±5.2

The physical characteristics of land use types and rubber plantation chronosequence: bulk density (BD), moisture content (MC), and porosity (PO). Land uses and rubber plantation years: NF: Natural forest, CA: coffee agroforestry, RP5: 5 years rubber plantation, RP10: 10 years rubber plantation, RP15: 15 years rubber plantation, RP20: 20 years rubber plantations, RP25: 25

years rubber plantation. SD= standard deviation. The analytical results were statistically significant at $P<0.05$. Means in columns followed by the same letter(s) are not significantly different at 5% level of significance.

Soil chemical characteristics

Soil pH

The soil pH was significantly affected by land use types and age of rubber plantation (Table 2). There was significance difference ($p<0.01$) in soil pH between the forest and all age categories of rubber plantations. Similarly, soil pH in old aged rubber plantation was significantly higher than early years of rubber plantation ($p<0.05$). The highest soil pH was recorded in the natural forests (6.5±0.10), followed by coffee agroforestry (6.1±0.25), while the lowest was recorded in RP5 (5.2±0.20) (Table 2).

Nitrogen and Phosphorus

The total nitrogen (TN) content of soils was significantly ($p\leq0.001$) different between land use types and ages of rubber plantation. Moreover, the soil nitrogen content of the old age rubber plantation was significantly higher than the early years of rubber plantation ($p<0.05$) (Table 2). The highest nitrogen content was recorded in NF (0.42±0.05%) followed by CA (0.37±0.03%) while the lowest value was recorded in RP5 (0.24±0.04%).

Available phosphorus content was significantly ($p<0.01$) affected by land use types and ages of rubber plantation. The highest available phosphorus was found in the natural forest (NF) (45.6 45.6±3.1 ppm), followed by CA (34.4±4.0), RP25 (32.3±3.1) and RP20 (36.3±3.0). The lowest soil available P content was recorded in RP5 (18.5±2.1 ppm). Thus, available P considerably increased with increasing age of rubber plantation in the study area.

Organic carbon and C: N

The organic carbon (OC) of the soils in the study area was significantly ($p\leq0.05$) affected by land use types and years of rubber plantation. The soil organic carbon in the older rubber plantation was significantly higher than the early year rubber plantation ($p<0.05$). The highest organic carbon content was recorded in NF (4.4±0.3%), followed by CA (4.3±0.3%) and RP25 (3.8±0.5%). However, low organic carbon was recorded in RB5 (1.42±0.2%) (Table 2). Therefore, organic carbon content substantially increased with increasing age of the rubber plantation in the study area. The observed high organic carbon in, NF, CA, and older age of rubber plantation was attributed to high tree biomass litter fall from the trees and shrubs on those land use types and old ages plantation sites.

The C:N ratio at 25-year stand (RB25) was significantly different from RP5 and RP10 ($p\leq0.05$), but similar with, NF, CA, RP20 and RP15. The highest C: N ratio was found in RP25 (11.7±0.9) followed by CA (11.6±1.6) and RP 20 (10.9±2.1), while the lowest value was recorded in RP10 (5.8±2.3). The result showed that C: N ratios considerably increased with increasing age of rubber plantation (Table 2).

Exchangeable bases

The soil exchangeable K^+, Na^+, Mg^{2+} and Ca^{2+} in the natural forest was significantly different from the early age of rubber trees ($p<0.01$). Similarly, the exchangeable bases in old age of rubber plantation were significantly different from the early aged rubber plantation ($p<0.05$). The highest soil exchangeable K^+ (2.2±0.1 cmol (+) kg^{-1}), Ca^{2+} (28.4±3.8 cmol (+) kg^{-1}), Mg^{2+} (7.2±0.8 cmol (+) kg^{-1}) was found in soils under natural forests (NF) and the highest Na was found in CA (0.38±0.02 cmol (+) kg^{-1}) and RP20 (0.38±0.02 cmol (+) kg^{-1}). However, the lowest exchangeable K, Ca, Mg, and Na were found in RP5 and RP10 (Table 2). Thus, the exchangeable bases (K^+, Na^+, Mg^{2+} and Ca^{2+}) increased with increasing age of rubber plantation

Cation exchange capacity (CEC) and Base cation saturation

There was a significant difference in CEC between forest (NF) and different age categories of rubber plantations, and with coffee agroforestry (CF) ($p<0.01$). The highest CEC was recorded in NF (48.0±1.8 cmol (+) kg^{-1}), followed by CA (36.4±2.4 cmol (+) kg^{-1}). Among rubber tree plantation of different ages, the highest CEC value was recorded in RB20 (35.6±1.6 cmol (+) kg^{-1}), followed by RB25 (34.4±3.2 cmol (+) kg^{-1}), while the lowest was recorded in RP5 (27.2±1.7). Therefore, cation exchange capacity substantially increased with increasing age of rubber plantation in the study area.

There was a significant difference in bases saturation between RP15 and early years of rubber plantation ($p<0.01$). The highest base saturation was recorded in RP15 (81.8±1.9%), followed by NF (79.3±6.7%), while the lowest was recorded in RP5 (63.6±7.9%) (Table 2).

Table 2: Soil chemical characteristics of the land use types and different age categories of rubber plantations.

Chemical characteristics	Land use types and rubber plantation chronosequence							Overall mean ±SD
	RP5	RP10	RP15	RP20	RP25	CA	NF	
pH	5.2±0.20c	5.4±0.20c	5.7±0.30b	5.9±0.1b	5.9±0.20b	6.1±0.25ab	6.5±0.10a	5.8±0.4
TN	0.24±0.04d	0.28±0.04c	0.34±0.05bc	0.34±0.04bc	0.32±0.04bc	0.37±0.03ab	0.42±0.05a	0.33±0.07
Ava.P	18.5±2.1d	20.7±3.7cd	24.7±4.7c	34.4±4.0b	32.3±3.1b	36.3±3.0b	45.6±3.1a	30.3±9.6
OC	1.42±0.2c	1.58±0.4c	3.2±0.3b	3.7±0.4b	3.8±0.5ab	4.3±0.3ab	4.4±0.3a	3.2±1.1
C:N	5.9±0.5b	5.8±2.3b	9.6±1.8a	10.9±2.1a	11.7±0.9a	11.6±1.6a	10.5±2.0a	9.5±2.8
K^+	1.1±0.01c	1.1±0.04c	1.2±0.09c	1.9±0.01b	1.8±0.10b	2.1±0.10a	2.2±0.1a	1.6±0.5
Na^+	0.19±0.02c	0.17±0.02c	0.28±0.02b	0.38±0.02a	0.37±0.01a	0.38±0.02a	0.36±0.02a	0.30± 0.09
Ca^{2+}	12.2±0.7c	12.6±2.4c	18.3±2.4b	18.6±1.7b	19.6±3.3b	20.5±0.6b	28.4±3.8a	18.5±5.5
Mg2$^+$	3.6±0.6c	3.9±0.6c	6.1±0.8ab	5.9±0.5b	5.2±0.5b	5.6±0.4b	7.2±0.8a	5.4±1.3
CEC	27.2±1.7d	27.7±2.7d	31.7±2.1c	35.6±1.6bc	34.4±3.2bc	36.4±2.4b	48.0±1.8a	34.4±6.9
BS	63.6±7.9b	63.8±3.5b	81.8±1.9a	75.4±7.5a	78.2±4.6a	78.7±5.4a	79.3±6.7a	74.4±8.6

Soil chemical characteristics of land use types and rubber plantation chronosequence. Chemical characteristics: pH ,total nitrogen (TN) (%), available phosphorous (Ava.P)(ppm), organic carbon (OC)(%), C:N, K^+(Cmol (+) kg^{-1}), Na^+(Cmol (+) kg^{-1}), Ca^{2+}(Cmol (+) kg^{-1}), Mg (Cmol (+) kg^{-1}), cation exchange capacity (CEC) (Cmol (+) kg^{-1}), base saturation (BS) (%). *Mean value of soil chemical characteristics of land use types with similar letter in row are not significantly different to each other at $p<0.05$. RP5 (5 year rubber plantation), RP10 (10 years rubber plantation), RP15 (15 year rubber plantation), RP20 (20 years rubber plantation), RP25 (25 year rubber plantation), NF Natural forest, CA (Coffee agroforestry)

Soil organic carbon stocks and soil carbon loss

Soil organic carbon stocks

The soil organic carbon stock in the NF was significantly different from early years of rubber plantation ($p<0.01$), but NF was similar with old years of rubber plantation (RP20 and RP25) and coffee agroforestry (CA) (Table 3). The highest soil organic carbon was recorded in NF (114.3±16.5 tone ha^{-1}) followed by CA (112.2±12.8 tone ha^{-1}) and RP25 (98.5±10.7 tone ha^{-1}), while the lowest SOC stocks was recorded in RP5 (59.4±10.8 tone ha^{-1}).

Soil carbon loss

The estimated total soil carbon loss as a result of conversion of natural forests to rubber plantation and coffee agroforestry ranges from 11 Mg C ha^{-1} y^{-1} to 0.1 Mg C ha^{-1} y^{-1} (Table 3).

Table 3: Soil organic carbon stocks, carbon loss and calculated potential carbon dioxide emission related to a change in land use (conversion from forest to different age of rubber plantation and coffee agroforestry .

Soil organic carbon stocks		Change vs Forest	
Land use types	OC stocks (tone ha^{-1})	C loss ((Mg C ha^{-1} y^{-1})	CO_2 loss ((Mg CO2eq ha^{-1} y^{-1})
RP5	59.4±10.8c	11.0	40.3
RP10	61.0±6.4c	5.3	19.5
RP15	79.4±7.9b	2.3	8.5
RP20	97.8±6.0a	0.8	3.0
RP25	98.5±10.7a	0.6	2.3
CA	112.2±12.8a	0.1	0.5
NF	114.3±16.5a		
Overall mean ±SD	88.9±23.4		

Land uses and different age categories of rubber plantation years: RP5: 5 years rubber plantation, RP10: 10 years rubber plantation, RP15: 15 years rubber plantation, RP20: 20 years rubber plantations, RP25: 25 years rubber plantation, CA: Coffee Agroforestry, NF: Natural forest.

Discussion

Bulk density

The increases in soil bulk density in the early years of rubber plantation (RP5 and RB10) could be attributed to soil compaction by farm machineries, particularly bulldozers during forest and land clearing activity and human movement during agronomic management practice. Further, early age rubber plantations are characterized by limited canopy covering capacity, hence don't adequately protect the soil against the direct raindrops impact and surface runoff, which in turn led to surface crust formation, clogging of the pores and loss of organic matter (Kassa et al., 2019). The presence of low soil bulk density on the old age of rubber plantation may be attributed to the presence of high organic matter input from tree canopy litter. This result was in accordance to the findings of Yasin et al. (2010) in Indonesia.

Soil moisture content

The observed high moisture content in NF, CF, and older age rubber plantations could be attributed to the presence of high soil organic matter and soil aggregate formation which, in turn, increases the water holding capacity of the soil. Similar, strong correlation between organic matter and soil moisture content has been reported by Kassa et al. (2017) and Mamo et al. (2021).

Porosity

The presence of relative high porosity in the natural forest is related with the presence of high organic matter and low bulk density. Similarly, Bufebo and Elias (2020) reported that, high soil bulk density is an indicator of low soil porosity and soil compaction; and soil porosity is positively correlated with organic carbon content. Further, intensity of soil management practice and soil organic carbon determines the soil porosity (Chimdi et al., 2012).

Soil pH

The soil pH steadily increased with increasing age of rubber plantation. This finding is in line with the findings of Yasin et al. (2010) and Zhou et al. (2017), who reported high soil pH in the old age of rubber plantation. The presence of high pH in the forest, coffee agroforestry, and old years of rubber plantation could be ascribed to microbial decomposition and releases of base cations from the accumulated tree leaf litters. The presence of lower pH in the early age of rubber plantation sites could be due to leaching of bases cation and removal of exchangeable bases by soil erosion from the rubber plant in the early stage of plant development. Similarly, Aweto and Moleele (2005) and Xu et al (2020) reported a decrease in soil pH on the early age of Eucalyptus plantation.

Total nitrogen

The observed higher total nitrogen in the forest, coffee agroforestry and old aged rubber plantation sites could be associated with the high seasonal litter fall from the woody trees. Similarly, Nigussie and Kissi (2012), Ufot et al. (2016) and Chemada et al. (2017) stated that the higher total N was obtained under forest land compared to other adjacent land use types. Further, the increase in total nitrogen with stand age could be attributed to the presence of large tree biomass and litter fall as age of plantation proceed, which not only afford adequate ground cover, but also act as a huge reservoir of nutrients, thereby preventing nutrients from being leached away from the soil. Similarly, Gautam and Mandal, (2013) reported that soil nitrogen concentration was positively correlated to soil organic carbon concentration. The low soil nitrogen content in early age of rubber plantation may be associated with high nitrogen uptake by the plant and leaching on the early years of rubber. This result is consistent with Zhou et al. (2017) and Yasin et al. (2010).

Phosphorous

The presence of high phosphorus in natural forest, coffee agroforestry and old age rubber plantation may be related to high organic matter input from the tree biomass, which in turn, improves organic P content in the soil. Similarly, an increase in soil P bioavailability with increase in age of Chinese fir plantation (Wu et al., 2020). However, Ekukinam et al. (2014) reported an increase in soil available P with decreasing age of rubber plantation.

Organic carbon and CN ration

The presence of relative high organic carbon in the forest, agoforestry and old ages of rubber plantation is associated with high tree litter fall in to the soil. Further, the presence of high C:N on forest, agroforestry and old age of rubber plantation can be associated with high organic carbon content on those land uses, and in the older age of rubber plantation. Similarly, Boakye (2015) reported low C: N ratios in the early periods of rubber cultivation.

Exchangeable bases

The presence of high exchangeable bases (K^+, Na^+, Mg^{2+} and Ca^{2+}) can be ascribed to the releases of exchangeable bases during microbial decomposition of litters on forest and afroforestry land use types and older age of rubber plantation sites. On the other hand, high uptake of exchangeable bases by trees, leaching and loss by erosion during the early periods of rubber cultivation could led to low exchangeable bases in RP5 and RP10. Similarly, Suzuki et al. (2007) and Akhabue et al. (2020) reported an increase in exchangeable bases (K^+, Na^+, Mg^{2+} and Ca^{2+}) with increasing age of tree plantation.

Cation exchange capacity and Base cation saturation

The observed high CEC in NF, CA, and older age rubber plantations can be related with the presence of high soil organic matter. Similarly, Ichikogu (2011) and Vittori Antisari et al. (2018) reported that CEC in soil increases linearly with increasing age of secondary forest. The presence of high BS in RP15, NF, CA, RP25 and RP20 may be associated with the presence of high litter fall from the trees and high pH on those land use types and old age of rubber plantation. This finding is in line with Vittori Antisari et al. (2018), who reported an increase in base saturation (BS) in the soil with increasing age of plantations.

Soil organic carbon stocks

The increases in SOC stocks on forest and agroforestry land use types and old age of rubber plantation was associated with the presence of high litter fall added to the soil from various species of trees and shrubs inside those sites. This finding is in line with the findings of Noori and Inamati (2017) and Kassa et al. (2017). Further, Arora et al (2014) reported an increase in soil organic carbon stocks with tree age. The observed low organic carbon stocks in the early periods of the rubber cultivation could be attributed to the loss of organic carbon by leaching and erosion, and high nutrient uptake by the younger rubber trees. The finding is in line with the findings of Arora et al (2014).

Soil carbon loss

The conversions of forest to other land use types have led to decreases in soil carbon loss. Similarly, Kassa et al. (2017) reported that soil carbon loss due to conversion of forest and agroforestry to cropland. The result also revealed that organic carbon loss significantly declined with the increase in the age of rubber plantation. This may be associated with high litter accumulation with increase of stand age of rubber plantation. Furthermore, the conversion of forest to rubber plantation and coffee agroforestry also led to an emission of carbon dioxide where the highest emission was observed in the early periods of rubber cultivation in the study area. This finding is in line with Kassa et al (2017), who reported a loss in CO_2 due to conversion of forest to cropland.

Conclusions

Rubber (*Hevea brasiliensis)* is a globally important commercial commodity. The soil physico-chemical characteristics and soil organic carbon stocks are significantly affected by the land use and different ages of rubber plantation. The soil fertility of older ages (RP20 and RP25) rubber plantation is comparable with the natural forest (NF) and coffee agroforestry (CA). However, the early ages of rubber plantation (RP5 and RP10) have a significantly lower soil fertility compared to forest, coffee agroforestry and older ages of rubber plantation. The organic carbon storage potential of older ages of rubber plantation is equivalent with the forest and coffee agroforestry, yet the soil organic carbon stocks of the early ages of rubber plantations were lower than forest, coffee agroforestry and older rubber plantations. Therefore, additional supplementary effort is required to maintain the soil fertility and organic carbon storage of rubber plantation at the early growth and development years.

Recommendations

- ✓ Supplementary nutrient and soil and water conservation measures need to be implemented at the early stage of rubber plantation.
- ✓ The impact of rubber tree chronosequence on biodiversity and species composition needs to be studied on the future.
- ✓ Studies are needed to assess the nutrient and carbon stocks level in the vegetation canopy of the rubber plantation chronosequence and the three land use types.

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