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Soil Acidification Vulnerability and Long-Term Trace Metal Depletion Under Rubber Tree Plantations in the Semi-Mountainous Region of West Côte d'Ivoire

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Abstract
The objective of this study was to assess the impacts of rubber cultivation on soil properties in the Tonkpi region, western Côte d'Ivoire. The study proceeded by comparing soils under rubber tree cultivation of different ages to those under other crops or fallow. The soils were sampled from a depth of 0 to 25 cm. The samples were dried and then sent to the central laboratory of the University of Man for physical and chemical analyses. Soil pH was measured with the multiparameter HANNA HI9829. Soil potentially toxic elements like As, Zn, Cu, Ni, Co, Cr, Mo, Fe, Se, Ca, Pb, K, Mn and V were analyzed, at the geological laboratory of the University Felix Houphouet-Boigny with a handheld NITON XL3t X-ray fluorescence analyzer. The results showed that soils from rubber-cultivated areas had a sandy loamy-clay texture, while those from the control area had a sandy-loamy texture. The soil pH was strongly to slightly acidic, with pH varying from 4.86 to 6.34, while the bulk densities varied from 0.51/g cm^3 to 0.62 g/cm^3. The redox potential of the soils was inferior to 400 mV ($E_h < 400$ mV). This study also revealed a general decrease in the potentially toxic element content of soils under rubber cultivation. The soil contents of Cr, Co and Cu were inferior to the limit of detection. The Pb, Mn and Ca concentrations were 4.81, 194.2 and 2140 $\mu g\ g^{-1}$, respectively, and these were significantly different from those of the other soils. This study provided a major insight into the effect of rubber cultivation in western Côte d'Ivoire.

Keywords: Potentially toxic element, pXRF, *Hevea brasiliensis*, heavy metal

1. Introduction

Hevea is a tree native to Amazonia, whose cultivation began in Southeast Asia and Africa at the end of the 19th century, and expanded at the beginning of the 20th century [1]. In Côte d'Ivoire, the cultivation of this tree began with Industrial Plantations in the mid-1950 century, at the instigation of the government. Several companies were then set up, including Société Africaine de Plantations d'hévéa (SAPH) in 1956, Compagnie des Caoutchoucs du Pakidé (CCP) in 1960, Société de Développement de l'Hévéa (SODHEVEA) in 1969, then transformed in 1973 by Société des Caoutchoucs de Côte d'Ivoire

(SOCATCI), and finally became Société des Caoutchoucs de Grand-Béréby (SOGB) in 1979 [2], [3]. Between the 1960s and the end of the 1980s, projects were set up in the village to develop village plantation. These plantations remained fewer in number [3] during this period and were necessarily organized around agro-industrial complexes, bringing together industrial plantation and primary latex processing plants [4], [5]. Following its adoption by the local population, rubber cultivation took off in Côte d'Ivoire, and is now considered an innovative project in the world of cultivation. This new crop was to grow even faster as the cost of coffee and cocoa collapsed [5].

For a long time, rubber production in the country was concentrated in the forest areas of the southeast, south and southwest, with a marginal production zone in the central west. The western part of Côte d'Ivoire, where the main crops are coffee, cocoa and rice, is increasingly planted with rubber tree.
Western Côte d'Ivoire is a semi-mountainous region characterized by a high aridity index, 1.59 [6], suggesting that the zone belonged to humid climate. Rubber tree is a high nutrient demanding crop especially during the immaturity phase of their growth and development [7]. Soil nutrients leaching has become very common under humid climate [8].

Therefore, this observation raised questions about the impact of this crop on soil quality in western Côte d'Ivoire. Indeed, the long-term cultivation of rubber trees results in a significant reduction in nutrients and a change in the biodiversity of microorganisms [9]. Consequently, this work was conducted to assess the long-term impacts of rubber cultivation on soil characteristics.

2. Materials and methods

The study was conducted in the semi-mountainous region of Man (Figure 1). The global positioning system receiver, model Garmin GPSMAP 64S, was used to collect the coordinates of the sampling points. Five (5) rubber plantations of different ages were selected: two (2) of 10-year-olds (H2 and H4), two of 30-year-olds (H1 and H5), and one of 21-year-olds (H3) (Figure 1). Around each rubber plantation, a control soil was selected, regardless of the type of crop (fallow or other crop, not bearing rubber tree as a crop). Soil samples were collected with an auger from a depth of 0–25 cm, and a composite sample was made from the three elemental samples (Buol et al., 2011) for each rubber plantation. Three (3) samples were taken from each rubber plot, and one (1) control sample was taken around each selected rubber plantation.

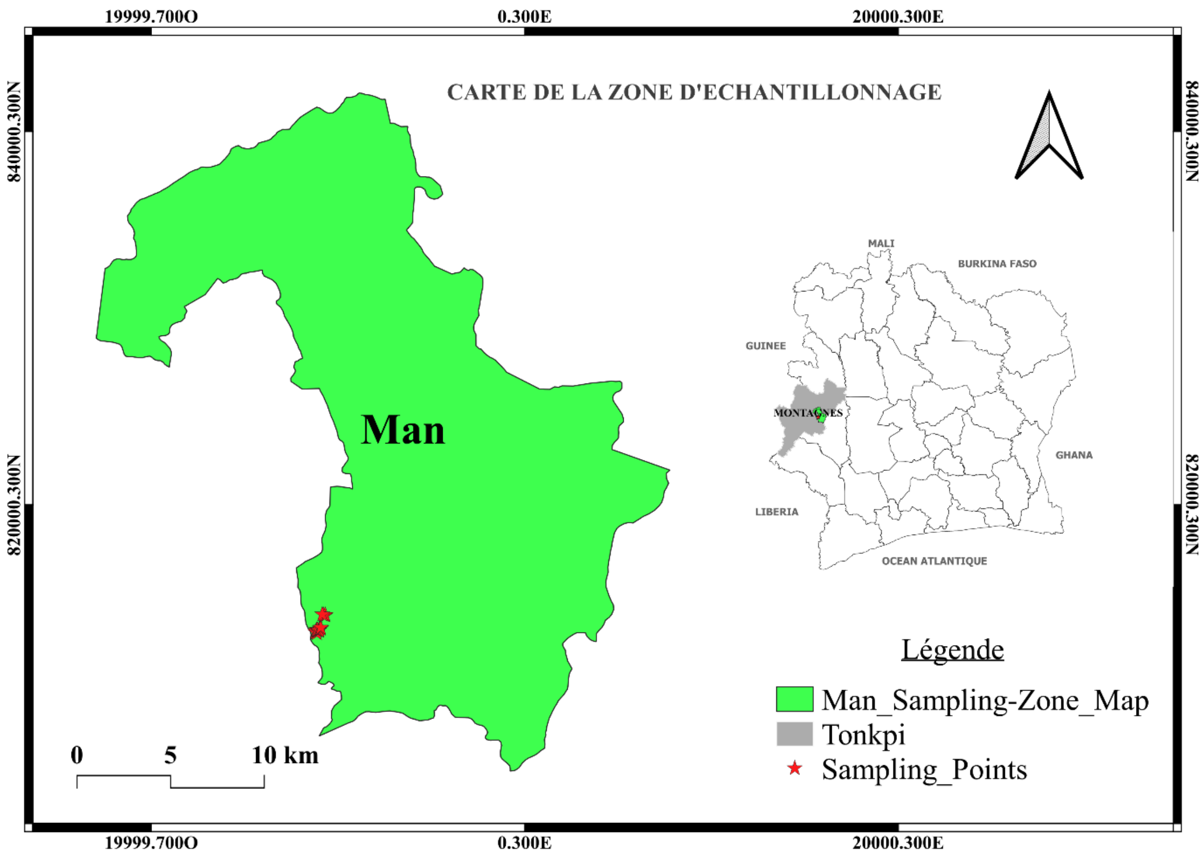

Figure 1: Study zone

The soil samples were carried in bags and then air-dried for three (3) days at room temperature in a drying room. Coarse particles were separated from the fine soil using a 2 µm round-meshed sieve. Fine soil samples were weighed and then conditioned for physical and chemical analysis.

The HANNA HI9829 multiparameter was used to determine soil redox potential and pH at the Central Laboratory of the university of Man, Côte d'**.** The pH and redox potential were measured in a 1:5 soil-water solution; 100 g of soil in 500 mL of distilled water (Husson et al., 2016).

The samples were analyzed using a portable NITON XL3t X-ray fluorescence analyser, at the Geology, Mineral Resources, and Energy Laboratory of the UFR des Sciences de la Terre et des Ressources Minières (STRM), Université Félix Houphouët-Boigny (UFHB), Abidjan (N'cho et al., 2022). The results obtained, specifically for the potentially toxic elements, were compared to the AFNOR NFU44-041 standard to evaluate their toxicity level.

QGIS software 3.32.2-1 to plot the map of the sampling zone. The statistical software Minitab 17.1.0 was used to analyze the collected data. For this purpose, a one-way variance analysis was carried out. Means comparison was done with the Fisher LSD Method at 95% confidence. A linear regression analysis was run using soil parameters as response variables and RT-grown soil age as a continuous predictor. Furthermore, the relationships between the oldness of the RT plantation and soil properties were assessed using Pearson correlation.

3. Results

3.1. Physical characteristics of the soils

The mean values for physical characteristics are reported in Table I. The granulometric test showed that the RT plantations had a sandy clay loam texture, while the control soils had a sandy loam texture. The bulk density (BD) of RT plantations decreased with age and land use. The soils of a 10-year-old RT plantation had bulk densities of 0.54 g/cm3 and 0.55 g/cm3 for RT4 and RT2. Those supporting 21-year-old rubber plantations had 0.53 g/cm3, and 30-year-old RT plantation soils had 0.51 g/cm3. The control soils, however, had higher bulk densities than the RT plantation soils; the highest was observed in Control 4 with 0.62 g/cm3, even though these observations were not significantly different from the ones of RT plantations. Soil samples were generally brown according to the Munselle colour chart.

Soil acidity level and oxidation reduction potential

The pH mean values of RT-grown soils varied from 4.86 to 5.30, while the control field soils' own varied from 5.39 to 6.34. The pH mean value of the control plots was 6.01, significantly higher than that of the RT-grown soils, which was 5.04 (Table II).

The redox potential is used to determine soil condition, highlighting variables such as soil oxidation and reduction. RT-grown soils' Eh varied from 236.2 mV to 253.0 mV, while the control field's soils were from 196.7 to 221.9 mV. The mean value of Eh RT-grown soil was significantly higher than that of the control fields with 245.04 mV and 204.38 mV, respectively.

Table I: Physical parameters of the soil

Site	**Bulk density** (g cm^{-3})	**Argile** (%)	**Limon** (%)	**Couleur**
RT1 (30 years)	0.51	20.3	12.7	Brown
RT2 (10 years)	0.54	21.34	11.96	Dark brown
RT3 (21 years)	0.53	20.5	10.5	Dark brown
RT4 (10 years)	0.55	22.17	7.33	Very dark brown
RT5 (30 years)	0.51	25	4	Brown
Control 1	0.60	10	4	Strong brown
Control 2	0.56	13	8	Very dark brown
Control 3	0.56	13	8	Very dark brown
Control 4	0.62	7.4	8.6	Very dark brown
Control 5	0.56	8.7	5.3	Very dark brown

Table II: Acidity levels and oxidation reduction potential (Eh) of control soils and grown rubber tree (RT)

Sites	**pH**	**Eh** (mV)	**Sites**	**pH**	**Eh** (mV)
RT1 (30)	4.86	245.5	Control 1	5.39	221.9
RT2 (10)	5.00	253.0	Control 2	6.34	196.7
RT3 (21)	5.30	236.2	Control 3	6.34	196.7
RT4 (10)	5.02	252.6	Control 4	5.66	209.6
RT5 (30)	5.03	237.9	Control 5	6.40	197.0
Mean RT	**5.04 b**	**245.04 c**	**Mean Control**	**6.01 a**	**204.38 d**

Mean values followed by a and b, c and d are statistically different at p = 0.05, means separation made with Tukey HSD test.

3.2. Potentially hazardous elements in the investigated soils

Elements with the potential to be poisonous are necessary for plants to operate physiologically. When present in large concentrations, they are regarded as inorganic pollutants, and can become hazardous. It can be seen that the mean values of trace metals in the control fields were significantly higher than the mean values in the RT plantations. By way of comparison, in this study, the trace metals detected in the sampled soils were: arsenic, zinc, copper, nickel, cobalt, chromium, molybdenum, iron, selenium, calcium, lead, potassium, manganese and vanadium (Table IV). Selenium (Se) was not detected in the RT-grown soils, nor in the control field soils. While Cr, Co and Cu had expressive values in the control soils with 52, 417 and 12.65 µg g^{-1}, respectively, their content was under the limit of detection in RT plantations soils. It should also be noted that the contents of Ca, Pb and Mn in the control field soils differed significantly from those of the RT plantations soils. However, the potentially toxic elements analysed in the sampled soils were below the AFNOR NFU44-041 standards. Cr, Co and Cu were not detected in the RT-grown soils while in the control soils were 52, 417, 12.65 µg $g^{-1}$for Cr, Co and Cu, respectively.

Table IV: Nutritional and potentially toxic elements content in sampled soils (mg kg^{-1})

Site	As	Ca	Fe	K	Mn	Mo	Ni	Pb	V	Zn
RT	0.67 a	1215 b	12 659.00 a	890.02 a	87.3 b	4.81 a	3.43 a	5.60 b	44.28 a	5.31 a
Control	2.80 a	2140 a	39319.39 a	1121.56 a	194.2 a	6.91 a	5.83 a	11.41 a	77.4 a	7.62 a

RT: rubber tree plantation, figures followed the same letters in the same column are not statistically different at p=0.05.

The linear regression analysis revealed the vulnerability of the soil acidity along with rubber plantation oldness: as plantation age increase, soil acidity also increases, inducing the decrease of soil pH (Equation 1). Equally, the regression revealed the same trend for calcium (Equation 2) and Mn (Equation 3) content. Contrarily, the potassium content increases along with rubber oldness (Equation 4). Figure 2 shows the approximate normality of the data distribution.

Equation 1: $pH = 5.064 - 0.0011x\ Age,$
Equation 2: $Ca\ (ppm) = 1613 - 19.9\ x\ Age$
Equation 3: $Mn\ (ppm) = 109.9 - 1.13\ x\ Age,$
Equation 4: $K\ (ppm) = 484 + 20.3\ x\ Age$

The test of correlation revealed that soil pH and Eh were significantly and negatively correlated, Ca content was significantly and positively correlated Mn content and pH.

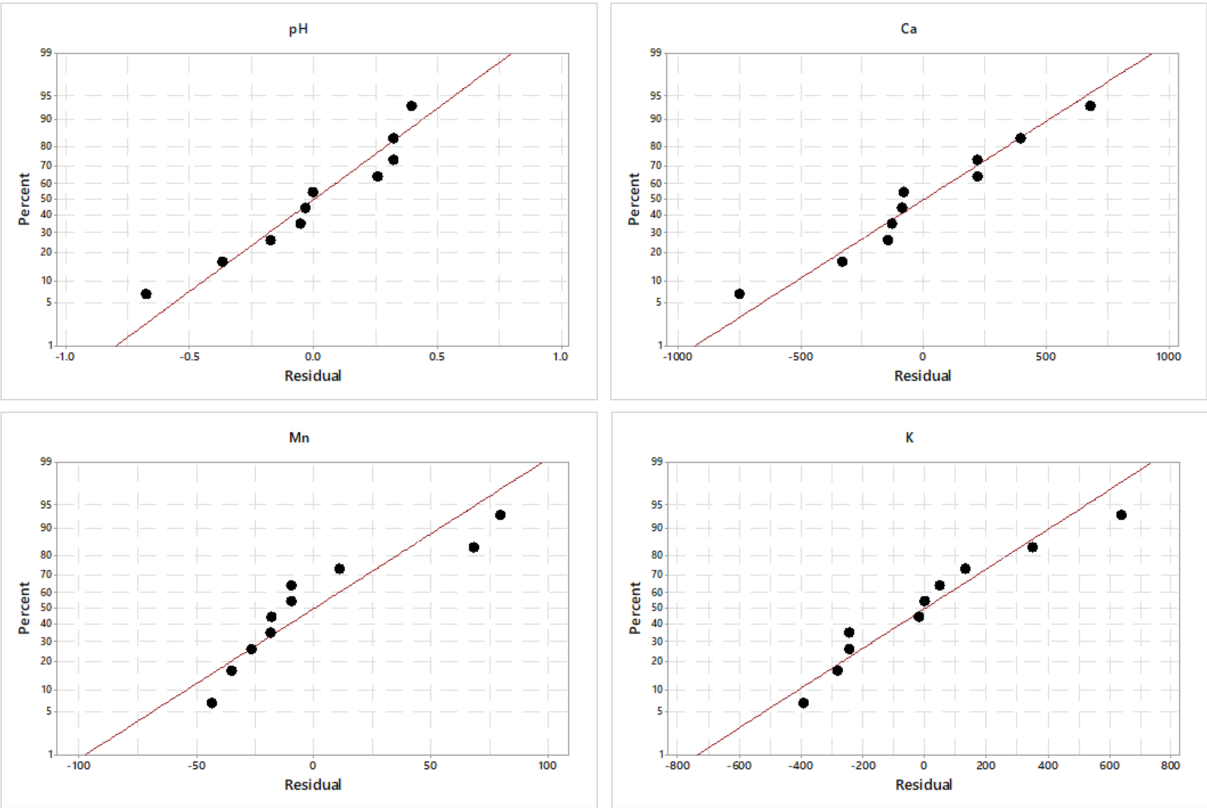

Figure 2: Normal probability plot for pH, Ca, K and Mn from rubber tree plantation.

4. Discussion

Physical characteristics analysis of studied soils is essential for understanding their composition and structure, as well as their agronomic potential and ability to supply nutrients to plants. In this study, the results of physical parameters such as bulk density, soil color and clay and silt content were evaluated for rubber tree (RT) plantations and surrounding control soils.

Soil particles size analysis revealed that the RT-grown soils had a sandy clay-loam texture, while the control soils had a sandy-loam texture. Silty-clay soils generally have good water retention capacity and high potential fertility, which can be beneficial to rubber cultivation. Previous studies reported that these types of soil texture are excellent and suitable for most crops, including RT [10]–[12].

Table V: Correlation matrix among essential soil trace elements.

	Mo	Pb	As	Zn	Cu	Ni	Co	Fe	Mn	Cr	V	Ca	K	pH	ORP
Mo	1.00														
Pb	0.34	1.00													
As	0.91*	0.22	1.00												
Zn	-0.39	0.58	-0.48	1.00											
Cu	0.93*	0.28	0.92*	-0.51	1.00										

Ni	-0.07	0.61	-0.27	0.47	-0.24	1.00									
Co	0.91*	0.33	0.92*	-0.39	0.90*	-0.15	1.00								
Fe	0.96*	0.36	0.93*	-0.43	0.95*	-0.08	0.98*	1.00							
Mn	0.72*	0.38	0.71*	-0.16	0.68*	-0.08	0.67*	0.73*	1.00						
Cr	0.83*	0.26	0.86*	-0.35	0.78*	-0.16	0.97*	0.92*	0.62	1.00					
V	0.94*	0.57	0.87*	-0.24	0.88*	0.12	0.88*	0.94*	0.79*	0.79	1.00				
Ca	0.49	0.13	0.54	-0.15	0.53	-0.39	0.44	0.49	0.90*	0.38	0.52	1.00			
K	0.23	0.64*	0.21	0.34	0.35	0.18	0.33	0.31	0.03	0.26	0.27	-0.08	1.00		
pH	0.43	0.25	0.46	-0.07	0.47	-0.26	0.51	0.52	0.88*	0.50	0.52	0.91*	-0.01	1.00	
ORP	-0.40	-0.41	-0.44	0.00	-0.50	0.19	-0.47	-0.50	-0.84*	-0.42	-0.55	-0.87*	-0.16	-0.95*	1.00

ORP: Oxydo-reduction potential

Bulk density is an indicator of soil compaction, which can affect root penetration and soil aeration, and is, therefore, an indicator of soil structure. The results showed that 10-year-old RT plantations had a higher bulk density than 20-year-old and 30-year-old RT plantations. This could be due to progressive soil compaction over time in older plantations, as a result of farming activities and frequent worker's traffic. Low bulk density facilitates root growth and the circulation of oxygen and water in the soil [13]. The bulk density of tropical soils increases with depth [14], [15], and according to the type of land use. Since all soil bulk densities were lower than 1.5 g cm^{-3}, then it could be stated that these soils were appropriate for optimum movement of air and water through the soil [13].

pH plays a key role in soil chemistry; for a given soil, it creates a favourable environment for mineral nutrition, plant growth and soil microorganisms activities [16], [17]. This role is best fulfilled when the pH is close to 7. The pH mean value in the control fields was 6.01, higher than the 5.04 in the rubber plots. This finding could imply acidification of the soil by rubber cultivation, detrimental to subsequent crops. However, acidic pH is a favorable parameter for rubber trees growth [16], [17].

Redox potential, a parameter that assesses the oxidation and reduction state of the soil, is influenced by water and soil weathering. Soil Eh range can be differentiated into oxic (>+400 mV), weakly reducing (+400 to +200 mV), moderately reducing (+200 to −100 mV), and strongly reducing (<−100 mV) conditions [18], [19]. Consequently, the edaphic environment of RT grown soils was weakly reducing while the one of the control fields varied from weakly to moderately reducing. The results showed that the soils had reducing environments, Eh < 400 mV. Furthermore, the average redox potential in the rubber plantations (245.04) was higher than in the control plots (204.38 mV). This could indicate greater biological activity and nutrient availability in the rubber plantations.

The linear regression showed that soil pH decrease was related to RT oldness. Acidification is a phenomenon that affects tropical soils. It has been observed that intensive cultivation of rubber plantations often causes a significant loss of soil fertility [20], which could impair soil microbial population and diversity [21].

The negative significant correlation between pH and Eh means that the decrease of pH imply an increase of Eh, which could create an unlivable soil environment for plant and microorganisms. In fact, both pH and Eh influence soils microbial activity, and are major drivers of soil/plant/microorganism systems [21], [22]. Generally, most cultivated soil Eh vary from 300 – 500 mV under aerobic conditions while most cultivated soils have a pH between 4 and 9 [22].

With regard to potentially toxic elements, their mean values in the control plantations were relatively higher than those in the rubber plantations. This would suggest that soils in control plantations were or are more exposed to sources of potentially toxic elements contamination, including the use of fertilizers, pesticides or other agricultural practices on control soils, especially for Cr, Co and Cu, which had zero levels.

On the other hand, it is important to point out that the means value of Ca, Pb and Mn in the control fields soils differed significantly from those in RT plantations. This may be attributed to natural soil variations or to specific agricultural practices applied in the control plantations, such as the use of fertilizers rich in these elements.

Finally, it should be noted that the potentially toxic metals analyzed in the soils sampled were below the reference standards set by AFNOR standards NFU44-041[23]. This indicates that potentially toxic elements levels in the soils studied do not exceed the thresholds considered harmful to human health and the environment according to these standards.

5. Conclusion

The study showed that there is a risk of soil fertility decrease under intensive rubber tree cultivation. It also revealed a decrease in the nutritional and potential toxic elements content of soils under rubber tree cultivation. However, it revealed deficiency of the soils in selenium. This study provides a major insight into the effect of rubber cultivation in western Côte d'Ivoire.

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