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Agro-Morpho-Pedological Evaluation of Soils under Hevea in Marginal Zones: The Case of the Departments of Man and Toumodi

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Among the ecological conditions of the environment allowing profitable rubber cultivation, rainfall and the physico-chemical characteristics of the soil are the most important. With this in mind, a study on the adaptability of rubber trees to new agro-morphopedological zones was conducted in the departments of Man and Toumodi. The methodology used to achieve this objective is the realization of pedological pits coupled with physico-chemical laboratory analyses. The open soil profiles reveal that the soils belong mainly to the Ferralsols class with distinctive characteristics, except for those of Kimoukro which belong to the Cambisols class. The Toumodi soils, with a

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sandy-clay texture (15-35% clay), have a high content of coarse sand (over 40%) and good internal drainage in the surface horizons. They are less dense (≤ 1 g/cm3), with a high coarse element load (40%). These soils are chemically rich with a slightly acidic pH. For the Man soils, the sandy-clay texture, with more than 50% clay, from surface to depth, was the most representative fraction. The coarse element load (≥ 50%) and bulk density (≥ 1.5 g/cm3) were more important. These strongly acidic soils are rich in nitrogen and carbon. Exchangeable bases and CEC are important, mainly, in the upper horizons. In addition, the soil profiles observed in these two departments revealed two major pedogenetic processes: reworking and rejuvenation. At the agronomic level, vegetative growth and rubber production of rubber trees were better in Man than in Toumodi. The physico-chemical characteristics of the soils indicate that the departments of Man and Toumodi are favorable for rubber cultivation, although the soils in Man department are more suitable for cultivation.

Keywords: Soils; adaptability; new rubber growing areas; Hevea brasiliensis; Côte d'Ivoire.

1. INTRODUCTION

The rubber tree, with the scientific name *Hevea brasiliensis* Muell Arg. (Euphorbiaceae), is a fruit tree, with a height of more than 30 meters and a circumference of 1 to 5 meters at maturity [1]. It originates from the Amazon basin in Brazil [2-3]. This species, which can be continuously tapped, is cultivated for its latex, whose rubber composition makes it easier to process, with a yield that is significantly higher than that of any other known latex plant species [4]. Global natural rubber production in 2018 is estimated at over 13 million tonnes [5], of which 88% is produced in Asia and 6% in Africa. Rubber cultivation in Côte d'Ivoire has developed spectacularly over the past few decades due to the subsidy of rubber plant production by the Hevea Development Fund (FDH), the increase in the purchase price of rubber in the field and, above all, the monthly income that it provides. Rubber occupies an important place in the Ivorian agricultural sector, the "engine of economic development" of the country, as it contributes a high proportion of export earnings. The number of rubber planters increased from 16,500 to 165,000 between 2005 and 2020 [6]. In the same direction, the cultivated area increased from 74,000 ha to 600,000 ha, an increase of 810%. This trend is confirmed by the increase in natural rubber production from 170,000 tonnes in 2005 to 949,000 tonnes in 2020 [6]. This prodigious progress makes the country the leading African producer of natural rubber and the fourth largest in the world, compared to 7th place previously. Despite this performance, rubber cultivation in Côte d'Ivoire is faced with increasing pressure from land and parasites (Corynespora spp, Loranthaceae, Fomès lignosus spp, etc.) in traditionally favourable areas, and also from the ageing of the orchard. It should also be noted that the master plan for the development of the rubber sector foresees a production of about two million tons of natural rubber over the next five years, and thus consolidate its dominant position in Africa. To reach this goal and meet the ever-increasing demand for natural rubber, two strategies can be adopted and consider joining the top three producers in the world. The first is to improve rubber productivity in traditional growing areas by optimizing latex harvesting systems in plantations, appropriate replanting techniques and by selecting better performing clones that are better adapted to local environmental conditions. The second strategy consists of extending the rubber cultivation areas to non-traditional zones, described as marginal. These so-called marginal areas are characterized, on the one hand, by a significant annual water deficit ranging from 400 to 600 mm of water and, on the other hand, by soils with coarse elements, armourstone slabs or sound rocks at shallow depths in some places [7-9]. However, rubber is a fairly demanding crop in terms of soil, due to its taproot system, and in terms of climatic factors, notably abundant and well-distributed rainfall (more than 1600 mm/year on average, [4]). The soil and climatic parameters in these new cultivation areas, which are of major importance for rubber, could be detrimental to its establishment, growth and future rubber production. Therefore, knowledge of these (soil and climate) factors is an important prerequisite for sustainable rubber production from an agronomic, economic and environmental point of view. This study was therefore initiated to assess the agricultural potential of soils for rubber cultivation in the administrative departments of Man and Toumodi in order to identify the main constraints to the productivity of these soils. More specifically, the aim was to evaluate the current physical and chemical characteristics of the soils of the two study sites and to study the behavior of rubber plants on them.

2. MATERIALS AND METHODS

2.1 Study Areas

The study was carried out in the respective localities of Zélé in the West and Kimoukro in the Centre of Côte d'Ivoire. The Zélé site is located between 7°20'00" and 7°30'00" North latitude and 7°30'00" and 7°40'00" West longitude in the administrative department of Man (Fig. 1). Kimoukro is located between 6°20'00" and 6°30'00" North latitude and 5°10'00" and 4°55'00" West longitude in the administrative department of Toumodi (Fig. 1). The climate of Man is tropical and humid [10,11]. Rainfall is monomodal with a long rainy season lasting eight months from March to October. During the decade (2007-2018), this locality received an average annual rainfall of about 1700 mm. The soils in Man are mainly Ferralsols, according to the working group WRB (2014) classification. Toumodi department is characterized by a transitional equatorial climate with two maxima and two minima [12,10]. The average annual rainfall is estimated at 1,200 mm, with an average temperature of 26° C and an average relative humidity of 77% [13]. The soils of Toumodi are quite varied. Ferralsols, Gleysols and sometimes Cambisols are found [14]. For this study, two types of plots according to age were chosen in order to make a comparative study of the productivity of the soils of the two localities. The cultivation techniques practiced around or within the plot and the types of cultivation guided this choice. All these investigations made it possible to determine two plots in each of these two localities, one of which was young, 2 to 3 years old, and the other, 6 years old or more, was being tapped.

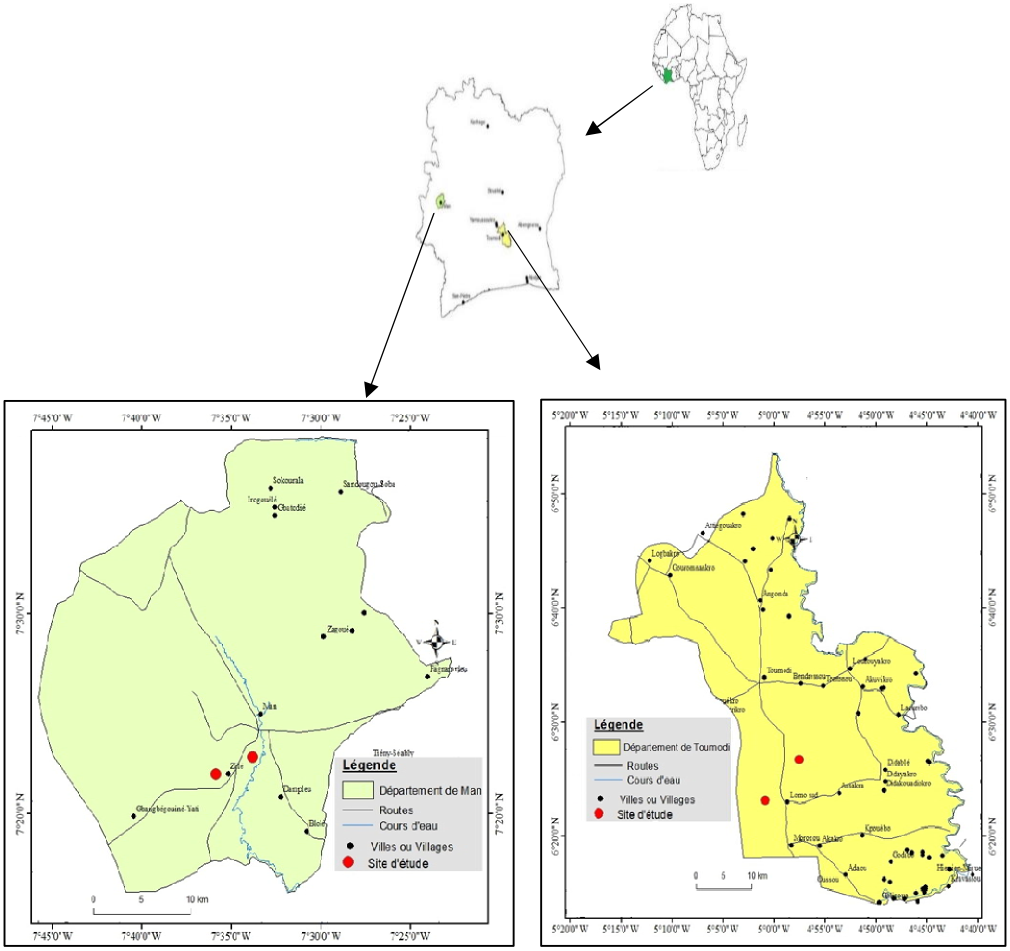

Fig. 1. Study areas

2.2 Plant Material

The plant material consists of *Hevea brasiliensis* clone GT 1. The GT 1 clone, originating from Indonesia, precisely from the Gondang Tapen region from which it takes its name, is a reference clone in Côte d'Ivoire. This clone, the most widely grown in Côte d'Ivoire, is characterized by an excellent grafting success rate and has a moderate to medium radial vegetative growth [15-17].

2.3 Study Methods

2.3.1 Data collection

2.3.1.1 Soil description and sampling under rubber trees

The soil data was collected during the dry season in the months of December to January, to avoid significant soil moisture. The first step was to open and describe the soil pits. A total of eight pits were opened, four per site, two on young plots (2-3 years old) and two on plots undergoing tapping (≥ 6 years old). Secondly, on each test plot, a series of soil samples from different horizons (0 - 20; 20 - 40 and 40 - 60 cm) was taken per pit for physico-chemical analyses in situ and in the laboratory. These analyses included the determination of the coarse element load, the soil texture determined by the Robinson-Köhn pipette method [18], the soil water pH measured on a soil-water suspension distilled in a ratio of 1/2, 5 (electrochemical method known as the "glass electrode" as described by [19] and organic carbon (C-Org) content determined by the Walkley and Black method [20], total nitrogen (Nt) by the universal Kjeldahl method [21]. Assimilable phosphorus (P-ass.), potassium (K) and exchangeable bases (calcium - Ca and magnesium - Mg) were determined by the ammonium acetate method buffered at pH 7.0; cation determinations were carried out by flame photometry for K^+, Na^+ and Ca^{2+} and by atomic absorption spectrophotometer (AAS) for Mg^{2+}. The cation exchange capacity (CEC) of the soils by the same method as above, but in this case it was the determination of the NH^{4+} ion, after quantitative desorption by K^+; in our case, we used the exchange reactions by successive decantation or discontinuous method, as described by [22]; Of these parameters, the organic matter (OM) content, containing on average 58 p. From these parameters, the organic matter (OM) content, containing on average 58% carbon (C), by the relation: OM (g.Kg-1) = C × 1.72; the ratio (C/N) was deduced.

The analysis of these results was based on the critical levels of interpretation of Boyer [23] and Landon [24].

2.3.1.2 Assessment of water stock in soils under rubber trees

The assessment of the water stock in soils was done by determining hydrodynamic properties of the soil, including parameters such as water storage capacity (SSC) and useful water reserve (Ru). The water storage capacity (SSC) of a soil is the maximum volume of water that it retains against the forces of gravity alone, i.e. after spontaneous drainage [25]. It is calculated from the formula established by GEPPA [26]:

$$CSE = Hv \times E \text{ and } Hv = Hp \times Da$$

With CSE: water storage capacity (mm), Hv: moisture content (%), E: soil thickness in (dm), Hp: moisture content by weight (%) and Da: bulk density.

The useful water reserve (Ru) is the maximum quantity of water retained at a given moment and accessible to the plant. It depends on the structure and texture of the soil, the rooting depth of the plant and the coarse element load. The useful water reserve (Ru) is also calculated from the formula established by GEPPA [26]:

$$Ru = 1/2 \times CSE$$

With Ru: useful water reserve (mm) and CSE: water storage capacity (mm).

2.3.1.3 Measurement of bulk density (Da)

Bulk density (Da) was measured using the sand method [27], this method was used for its ease of use. The sand method consists of digging a cavity in the soil inside a metal plate fixed parallel to the soil surface by stakes. All the soil is collected to determine the dry weight. The cavity is then filled to excess with previously graded sea sand. The surface of the plate is shaved and the excess is collected in a bag. In the laboratory, the residue is weighed and the quantity of sand poured in is determined. The Da is the difference between the initial weight of sand and the weight of the residue. The marine sand was first desalted by soaking in tap water, air-dried and sieved successively with 2.1 and

0.8 mm square-mesh sieves. At the end of this treatment, two dimensional classes (2 - 1 and 1 - 0.8 mm) of dry and flowing sand are obtained. The more abundant class with a density of 1.56 was used for bulk density measurements. Sand packages of 2.5 kg were made up for the field measurements. These measurements were carried out in the surface layer (0 - 20 cm) of the soil, through which most of the absorbing hairs of the rubber tree run. Three (3) measurements (replicates) were made per plot (0.5 - 1 ha). The bulk density (Da) is determined according to the equation:

$$Da = P / V$$

Da: bulk density (g/cm3), P: dry weight of the sample (g) and V: volume of the sample taken and dried (cm3).

The volume (V) of the collected and dried sample is determined by the equation:

$$V = [(\text{Weight of graded sand} - \text{Weight of remaining sand})] \times 1.56$$

2.3.2 Agronomic data

2.3.2.1 Radial vegetative growth of rubber trees

The radial vegetative growth of rubber trees was determined by annual measurements of the trunk circumference of the trees at 1 m from the ground for young plots (2 to 3 years old) and at 1.70 m for tapped plots (≥ 6 years old), using a tape measure.

2.3.2.2 Rubber production from tapped plots

Rubber production was estimated from the weighing of rubber per elementary plot, carried out every four weeks. The transformation coefficient per treatment was determined and made it possible to obtain, from the fresh weight (FW), the dry weight (DW) of rubber, in grams per tree per tapping ($g.a^{-1}.s^{-1}$), which reflects the intrinsic value of the tree in producing rubber.

2.3.3 Statistical analysis of the data

The mean values of the different parameters studied per site and per plot were subjected to a one-factor analysis of variance (ANOVA 1) at the 5% probability level, in order to observe possible significant differences or not. When a significant difference was noted between the factors considered for a given character, the test of the smallest significant difference (LSD) was performed. STATISTICA software version 7.1. was used to carry out all these analyses.

3. RESULTS

3.1 Soil Parameters

3.1.1 Morpho-pedological characteristics of the soils of the two study sites

3.1.1.1 Color of the different horizons of the soil profiles

Determination of the color of the different horizons of the soil profiles revealed variously colored patches of hydromorphism (7.5 YR 5/8; 10 YR 5/6; 10 YR 5/8 and 10 YR 4/6), which can be observed in the lower topographical positions (mid and lower slopes). These soils have been affected by hydromorphy at depth and the consecutive horizons of the observed profile are of type B.

3.1.1.2 Grain size composition of the observed soil profiles

Table 1 presents the physical characteristics of the soil at depths of 0 - 20, 20 - 40 and 40 - 60 cm at the two study sites. The particle size composition of the soils revealed that sand (59.7% on average in Man and 65.05% on average in Toumodi) is, in general, the most representative particle size fraction in the topsoil (0 - 20 cm) regardless of the study site and type of plot. Clay contents (49.05% on average in Man and 36.5% on average in Toumodi) were obtained in the deeper horizons. In these soils, silt is the least represented fraction.

3.1.1.3 Soil coarse matter loadings in the two localities

Fig. 2 shows the distribution of soil coarse matter loadings under rubber cultivation for the Man and Toumodi sites. On the soils of the young plots, the proportion of coarse elements was higher in Man than in Toumodi. These values were 56.59% for the soils in Man compared to 38.25% for those in Toumodi. In the bleeding plots, the coarse element load was relatively low (≤ 10%). Statistically identical, the values the results were 8.45% in the Man soil and 8.04% in the Toumodi soil.

Table 1. Granulometric composition of the different horizons of the soil profiles

Site	Type of plot	H (cm)	Granulometry (%)			Texture
			C	Lf + Lc	Sf + Sg	
Man	Young (2-3 years)	0 – 20	25	14,5	60,5	Silty-Clay-Sandy
		20 – 40	41,1	10,3	48,6	Clay-Sand
		40 – 60	47,3	13,1	39,6	Clay
	Tapping (≥ 6 years)	0 – 20	25,3	15,8	58,9	Silty-Clay-Sandy
		20 – 40	26,2	15,2	58,6	Silty-Clay-Sandy
		40 – 60	50,8	9,7	39,5	Clay
Toumodi	Young (2-3 years)	0 – 20	12,8	16,3	70,9	Silty-Sandy
		20 – 40	21	13,6	65,4	Silty-Clay-Sandy
		40 – 60	25,6	10,2	64,2	Silty-Clay-Sandy
	Tapping (≥ 6 years)	0 – 20	20,6	18,4	61	Silty-Clay-Sandy
		20 – 40	34	16	50	Silty-Clay-Sandy
		40 – 60	47,4	9,9	42,7	Clay

H: Horizon, C: Clay, Sf: fine Sand, SC: Coarse Sand, Lf: fine Loam, Lg: Coarse Loam

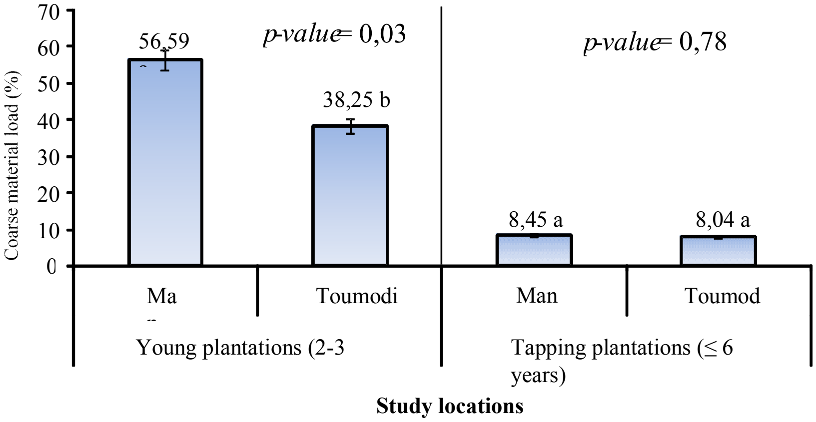

Fig. 2. Distribution of the coarse element load of the soils of the Man and Toumodi sites

3.1.1.4 Evolution of the water storage capacity of the soils of the study sites

The seasonal evolution of water storage capacity (CSE) of soils under rubber cultivation for plots in Man and Toumodi for the periods April to December 2014 is presented in Fig. 3. The analysis of variance (ANOVA) to the two controlled factors, namely locality (Man and Toumodi) and observation period (April to July and October to 2014), showed that there is a significant effect ($p < 0.05$) of these factors on the hydrodynamic parameter (CSE). Analysis of Fig. 3 indicates a seasonal fluctuation in the water storage capacity of the soils at the study sites. The highest values of SSC were obtained at the beginning of the short rainy season (October 2014) and at the end of the long rainy season (July 2014). However, the highest mean values were obtained in October 2014 in Man and are 559.25 ± 40.87 mm for the bleeding plots (≤ 6 years) and 467.32 ± 67.29 mm for the young plots (2 - 3 years), respectively. In contrast, in July 2014, the highest values were 318.49 ± 11.08 mm and 260.02 ± 13.25 mm in the bleeding and young man plantations respectively. From April to December 2014, mean SSC values were well below 100 mm for all sites.

3.1.1.5 Evolution of the useful water reserve (Ru) of the soils of the two study sites

Fig. 4 shows the evolution of the useful water reserve (Ru) of the soils under rubber cultivation in the Man and Toumodi plots for the period from April to December 2014. The ANOVA with Ru values of the two controlled factors, namely locality (Man and Toumodi) and observation period (April to July and October to December 2014), showed that there is a significant effect ($p < 0.05$) of these factors on this hydrodynamic parameter (Ru), regardless of the part of the study area. Relative to SSC, Ru showed higher values in October and July 2014. In October 2014, the highest average soil Ru values obtained at the Man site were 219.62 ± 20.87 mm for the bleeding plantations and 122.67 ± 16.58 mm for the young plantations. However, the average Ru values measured in April and December 2014 were below 50 mm at all sites.

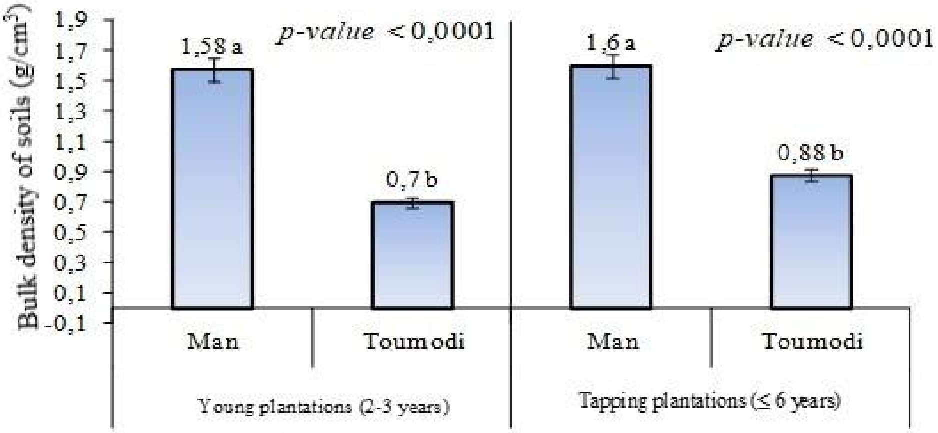

Fig. 3. Evolution of the water storage capacity of the soils of the sites

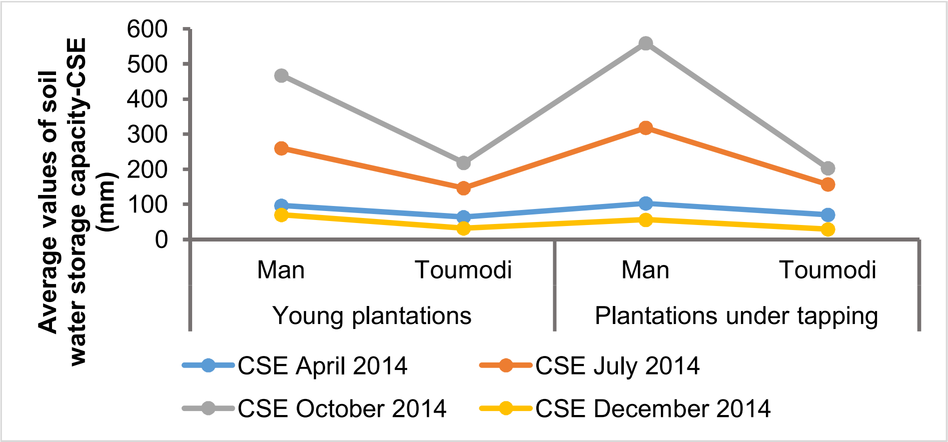

Fig. 4. Evolution of the useful water reserve (Ru) of the soils of the study sites

3.1.1.6 Bulk density of soils at the two study sites

The study of the apparent density (Da) of soils under rubber trees presented in Fig. 5 shows statically different values (p-value < 0.0001), whatever the locality (Man and Toumodi) and the age of the plot (young or tapped). In young plots, these values are 1.58 g/cm3 for Man and 0.7 g/cm3 for Toumodi. For plantations undergoing tapping, the average bulk density values are respectively 1.6 g/cm3 for the Man soils and 0.88 g/cm3 for the Toumodi soils.

3.1.1.7 Soil typology of the Man and Toumodi localities

The description of the open cultivation profiles on the different plots has made it possible to identify a soil typology. Thus, in the young plot in Man, Amphiarenic Ferralsol type soils are observed on the upper slope and Endoplinthic Pseudogleyic Ferralsol on the mid-slope. In the bleeding plot, Colluvicarenic Ferralsol soils are found on the mid-slope and Pseudogleyic Ferralsol on the lower slope. In Toumodi, the soils are of the Amphiarenic Ferralsol manganiferric type on the upper slope and Endoarenic Ferralsol manganiferric on the mid-slope for the young plot. In the bleeding plot, Pseudogleyic Cambisol soils were identified in the upper slope and Lixic Pseudogleyic Cambisol in the mid-slope.

3.1.1.8 Chemical composition of the soil samples collected

Table 2 shows that the Man soils are classified as very strongly to moderately acidic with pH values ranging from 4.5 to 6.5. In contrast, the Toumodi soils are moderately acidic, pH ($5.1 \leq pH \leq 6.5$). The organic matter (OM) content was moderately higher at the Man sites ($0.91 \leq OM \leq 2.93$) than at Toumodi ($0.56 \leq OM \leq 2.68$). Moreover, this content decreases with soil depth regardless of the study site. Table 2 also reveals that the total nitrogen content is very low ($N < 1\%$) in both the Man and Toumodi soils. Nevertheless, in the surface layer (0-20 cm), the Man soil is relatively rich in nitrogen (0.14%). A similar correlative variation in the rate of organic matter mineralisation (C/N) is observed, irrespective of the locality and depth of the soil. The adsorbent complex of the soils of the Man and Toumodi plots is characterised by a cation exchange capacity qualified as very low ($CEC \leq 5$) to low ($5 \leq CEC \leq 10$) which is fairly constant over all the samples analysed. On tapped plots (≤ 6 years old), this complex is moderately supplied with calcium ($1 \leq Ca2+ \leq 2.5$), and is deficient in magnesium (Mg2+), whose recommended optimum content for tapped rubber trees is ($1 \leq Mg \leq 1.5$ cmol.kg-1). The potassium content is very low ($0.1 < K+$), regardless of the plot and the locality.

3.2 Agronomic Parameters

3.2.1 Vegetative growth of rubber trees

The analysis of variance of the vegetative growth of the rubber trees observed through the average annual circumference indicates statically different values regardless of the locality and age of the plot (Fig. 6). For young plots of 2 to 3 years old, the average tree circumference is 16.40 cm in Man compared to 7.29 cm for the Toumodi plot. In the tapped plantations, Man still has the best average circumference values (59.47 cm), while Toumodi has a value of 52.18 cm.

3.2.2 Average annual production of rubber plantations

The average annual rubber production expressed in grams per tree and per tapping ($g.a^{-1}.s^{-1}$), over the five years of the experiment (tapping carried out in a half-spiral every three days) was 65.93 g in Man and 43.94 g in Toumodi (Fig. 7).

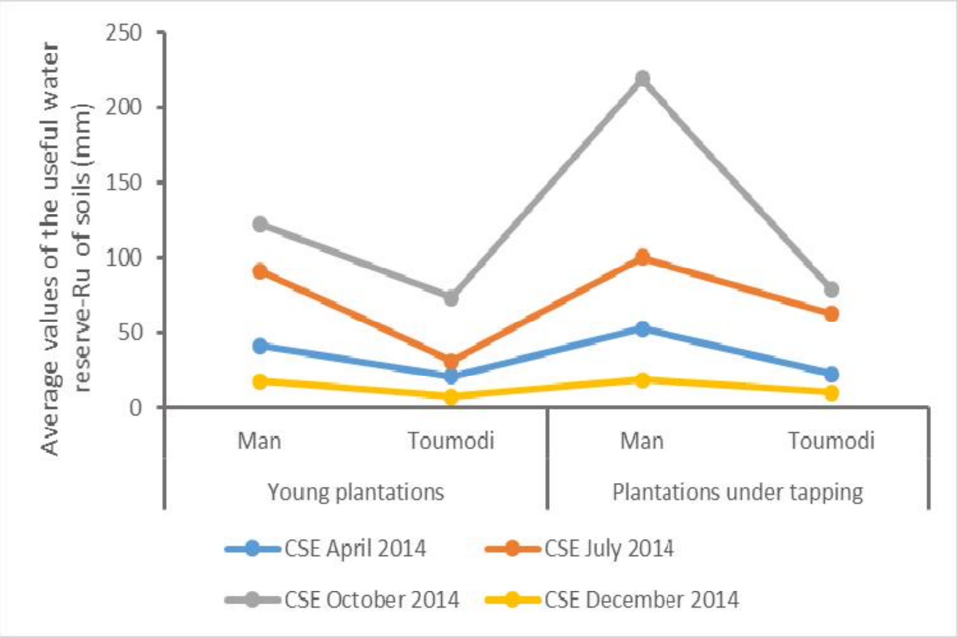

Fig. 5. Apparent soil density at Man and Toumodi sites

Table 2. Proportion of chemical elements in different soil horizons

Locality	Type and age of plots	Horizons (cm)	MO (p.c.)				Absorbent complex(cmol/kg)			
			pH	C	N	C/N	CEC	Ca^{2+}	Mg^{2+}	K^{+}
Man	Young (2 - 3 years)	0 – 20	4,5	1,70	0,14	12,14	9,84	0,52	1,21	0,01
		20 – 40	4,6	0,72	0,07	10,28	9,20	0,64	0,44	0,02
		40 – 60	5,4	0,53	0,06	8,83	10,40	1,59	0,87	0
	Tapping (≥ 6 years)	0 – 20	5,7	1,70	0,14	12,14	5,20	1,29	0,74	0,02
		20 – 40	6,4	0,88	0,08	11	3,20	1,69	0,47	0,01
		40 – 60	6,0	0,78	0,07	11,14	4,80	1,94	0,77	0,01
Toumodi	Young (2 - 3 years)	0 – 20	6,4	0,78	0,08	9,75	5,68	0,99	0,55	0,18
		20 – 40	5,3	0,59	0,06	9,83	6,88	0,69	0,19	0,04
		40 – 60	5,1	0,33	0,03	11	7,84	0,57	0,41	0,04
	Tapping (≥ 6 years)	0 – 20	6,4	1,56	0,14	11,14	10,08	5,76	0,85	0,17
		20 – 40	6,4	0,59	0,06	9,83	6,48	1,67	0,42	0,10
		40 – 60	6,5	0,35	0,03	11,66	12,48	1,03	0,54	0,14

%: percentage; C: Carbon; N: Nitrogen; C/N: carbon/nitrogen ratio; CEC: Cation exchange capacity; Ca^{2+}: Calcium ion; Mg^{2+}: Magnesium ion; K^{+}: Potassium ion

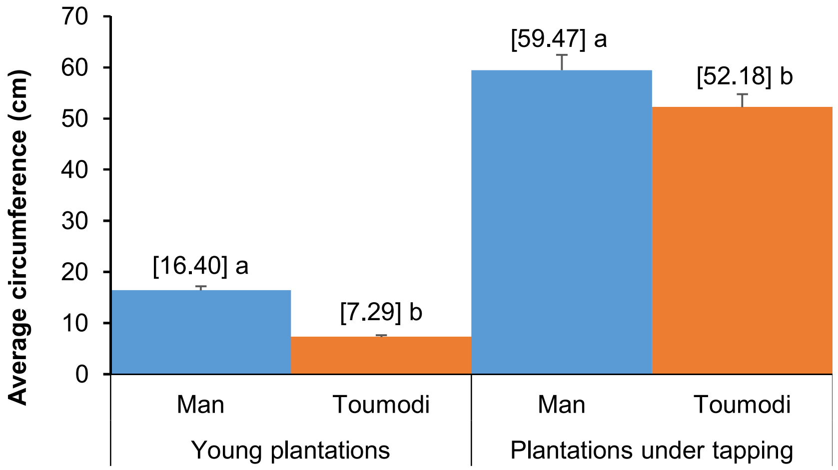

Fig. 6. Average circumference (cm) of rubber trees in both locations

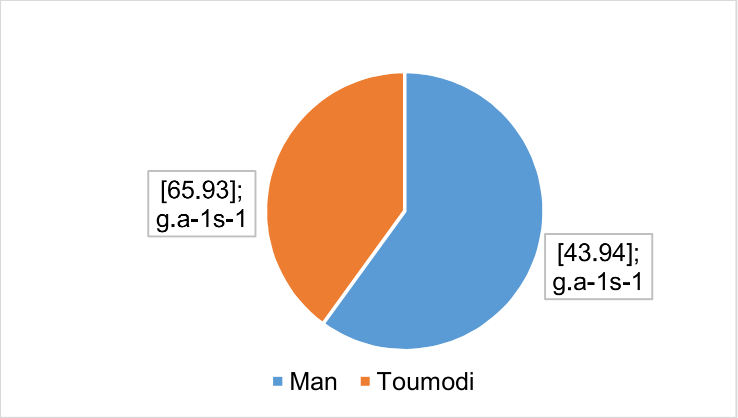

Fig. 7. Average annual rubber production (g.a^{-1}.s^{-1}) of Man and Toumodi rubber plantations

4. DISCUSSION

4.1 Physical and Chemical Characteristics and Agricultural Potential of Man and Toumodi Soils for Rubber Cultivation

The pedological study carried out on the experimental sites (young plot and tapped plot) reveals that the majority of the open soil profiles belong to the Ferralsols class (according to the WRB version 2014 [28]) with distinctive characters, except for the soils observed at Kimoukro (Toumodi) of the Cambisols class. The soils observed in Toumodi are very rich in sand and mainly in coarse sand (up to more than 40%) in the surface horizons (0 -20 cm and 20 - 40 cm). This high content of coarse sands makes the soil light and filtering, which could give it a low structural stability, thus inducing a high sensitivity of this soil to physical (erosion) and chemical degradation. This result corroborates the conclusions of Koné *et al* [29] on the quality of soils in the humid savannah of Côte d'Ivoire. However, on the surface of the soils encountered, lateritic cuirasses can, in places, form a natural protective layer, reducing evaporation and slowing down erosion by breaking up the surface flow [30,31]. It should be noted that in rubber trees, a sandy-clay texture (15 to 25% clay) corresponds to borderline or even mediocre conditions for the plant. For Man soils, the sandy-clay texture, sometimes with more than 50% clay, from the surface to the depth, was the most representative fraction. This high clay content in the surface horizons of soils could be due to a colluvium phenomenon and consequently induce a much more compact structure, thus making the soil asphyxiating. Also, Hénin et al [30] report that clay, a plastic, water-hungry and binding substance, is a cohesive element unlike sand. Another disadvantage of clay soils is the reduction of the available water domain or space when the fine elements increase [32]. However, according to [4,3], a clay soil with more than 55% clay throughout its depth offers very favorable conditions for rubber trees, provided that the soil is well aerated, porous and very deep. The high clay content of Man's soils is therefore not an obstacle to the development of rubber trees. On the different study sites (Man and Toumodi), two major pedogenetic processes were highlighted: reworking (coarse element load) and rejuvenation in the deeper horizons. Reworking, which is much more pronounced in the Man soils (≥ 50 p.c.), is the presence of a horizon rich in coarse elements (cuirass debris, ferruginous gravels, more or less blunt and ferruginised quartz gravels and pebbles). According to Avenard *et al* [12], Boyossoro et al [33] and Akanza [34], most of the Man plantation is established on soils characterized by the presence of a gravelly horizon close to the surface, which mark the soil dynamics not only by their number and size, but also by their composition and shape. According to Compagnon [4], the abundant coarse elements could constitute obstacles to root development and, by their volume, reduce the water reserves of the soil. Also, for soils with horizons whose coarse element load varies from 30 to 50%, fertility could be significantly reduced, especially if the stony layers contain more than 30% coarse elements over more than 20 to 30 cm in the upper horizons of the profile [35-37]. Furthermore, outcrops of lateritic cuirasses are frequent in Toumodi and give the cultivation profile a very high degree of heterogeneity. These soils are low in humus, very acidic and rather poor in chemical elements. They are therefore suitable for relatively undemanding crops. Their relatively shallow depth and low clay content give them a low water retention capacity. These edaphic characteristics, which are really limiting factors for agricultural activity in this area, require certain precautions for rubber cultivation. Rejuvenation is expressed by the presence of variously colored spots (7.5 YR 5/8; 10 YR 5/6; 10 YR 5/8 and 10 YR 4/6) in the soils, which indicate poor internal drainage at depth. This poor internal drainage would be linked to the fact that the water in the soil does not circulate correctly and this can create redox phenomena, which can cause asphyxiation of the plants, as has been reported [38]. In addition, the depth of the soil, mostly greater than 1 m, does not appear to be a limiting factor for the growth and development of rubber trees on these two sites. The apparent density of soils under rubber trees (in young plots or in tapping) shows statically different values whatever the locality. Soils in Man (1.6 g/cm^3) are denser than those in Toumodi (0.88 g/cm^3). This implies a tendency for the Man soils to be compacted, hence the high clay and coarse element content. On the other hand, the lower bulk density values at Toumodi reflect good soil aeration [39,40]. From a chemical point of view, the majority of the observed soils have a strongly acidic pH ($4.5 \leq$ pH ≤ 5.5) to acidic ($5.5 \leq$ pH ≤ 6.5). According to Landon, [41], at low pH values (very acidic soil), many adverse phenomena could occur in the soil, such as: decreased nitrification, phosphorus deficiency, aluminium or manganese toxicity, low mobility of organic pollutants and high availability of some heavy metals. These phenomena could be an obstacle to the vegetative growth and future production of young rubber plants. However, Compagnon [4] reports that the rubber tree is a very hardy plant, capable of great adaptability, which gives it tolerance to soil pH, to the extent that the rubber tree grows satisfactorily even at pH values between 4 and 6.5. Furthermore, the lack of chemical elements in the soil cannot be an obstacle to the establishment of the rubber tree, if good physical conditions are also achieved [4]. In rubber, the physical properties of the soil (depth, texture, aeration, water retention capacity, etc.) are more important than the chemical fertility of the soil itself. Indeed, compared to other crops (cocoa, coffee, tobacco, etc.), rubber trees are better able to tolerate soils with low fertility potential.

4.2 Vegetative Behavior of Rubber Trees

The vegetative behavior of the trees was assessed by comparing the average values of the isodiametric circumference of the trunk at 1 m and 1.70 m from the ground in each of the plots in the two localities (Man and Toumodi). It was found that in young plantations of 2 to 3 years old, the average circumference of the trees was 16.40 cm in Man compared to 7.29 cm in Toumodi. In the tapped plantations, Man still has the best average circumference values (59.47 cm). These results show that the rubber trees develop better in Man than in Toumodi. This difference in tree behavior could be explained by the different soil types in the two localities, from a physical and chemical point of view, and also by the high and well-distributed rainfall in Man. Indeed, as mentioned above, the soils observed in Toumodi are very rich in sand, particularly coarse sand. This high content of coarse sand makes the soil filtering and light, which could give it low structural stability, thus making it highly sensitive to physical (erosion) and chemical degradation. This coarse fraction therefore corresponds to borderline or even mediocre conditions, with medium dry seasons (one to two months) for rubber trees. In contrast, at Man, clay was the most representative fraction along the entire length of the open profiles. Compagnon [4] reports that a high clay content (≥ 55%) in the soil throughout the depth of the profile does not hinder the development of rubber trees. Furthermore, although rubber is generally considered to be a hardy crop that can adapt to many situations, its growth and yield level are nevertheless conditioned by certain climatic, environmental and soil characteristics. Climatically, a rainfall regime averaging between 1500 mm and 3000 mm per year is considered suitable for the growth and yield requirements of the rubber tree. Below 1500 mm per year, the survival of seedlings may be compromised, and tree growth may be significantly slowed. Above 3000 mm per year, the frequency of rainfall can be a limiting factor for yield because of the production losses caused. Here, there is a relative homogeneity of rainfall levels within the two study areas. The annual rainfall totals are, in fact, within the range of the rubber tree's needs. In terms of soil characteristics, there are also significant differences between the two areas. Thus, climatic variability in these two agro-zones (Man and Toumodi) could also contribute to explain this difference in growth observed. This explains and confirms the results obtained on the production of tapped rubber trees in Man (65.93 $g.a^{-1}.s^{-1}$) and Toumodi (43.94 $g.a^{-1}.s^{-1}$).

5. CONCLUSION

The results obtained at the end of the study on the characterization of the physico-chemical parameters of the soils of the departments of Man and Toumodi allow the following conclusions to be drawn.

1. The soil profiles reveal that the soils belong mainly to the Ferralsols class with distinctive characteristics, except for those in Toumodi, particularly in Kimoukro, which belong to the Cambisols class.

2. The Toumodi soils, with a sandy-clay texture (15-35% clay), have a high sand content and good internal drainage in the surface horizons. These soils are less dense than those observed in Man. Toumodi soils are slightly acidic and have a high nitrogen and exchangeable base content.

3. Despite some variability, the edaphic characteristics of Man (richness, texture, depth) seem compatible with sedentary agriculture.

4. For the Man soils, the sandy-clay texture was the most representative fraction. The coarse element load (≥ 50 p.c.) and bulk density (≥ 1.5 g/cm3) were more important. The soils in this department, rich in

nitrogen and carbon, are strongly acidic. Exchangeable bases and CEC are important, mainly, in the upper horizons.

5. Agronomically, the development of rubber trees and rubber production are important in the department of Man.

Given the agroedaphoclimatic requirements of rubber for good plant development, the soils of Man and Toumodi Departments are compatible with rubber cultivation, although those of Man Department appear to be more favorable to rubber farming.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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