Physicochemical Characterisation of Hydromorphic Soils under *Fleroya stipulosa* (Rubiaceae), a Vulnerable and Highly Medicinal Plant in Cameroon

Roland Nnomo Douanla[1][2]*, Bernard Palmer Yerima[2], Victor François Nguetsop[1], Adalbert Adibime Onana[2] and Bertine Tiokeng[1]

[1]Laboratory of applied Botany (LAAB), Plant Biology Departement, Faculty of Sciences, University of Dschang Po Box: 67, Dschang, Cameroun
[2]Laboratory of Soil Analysis and Environmental Chemistry (LASAEC), Soil Sciences Department, Faculty of Agronomy and Agricultural Sciences, University of Dschang Po Box: 67, Dschang, Cameroon

Abstract		**Original Research Article**

This study aimed at characterising hydromorphic soils under *F. stipulosa* in Cameroon. A representative soil profile of its realized niche was excavated, and soil samples collected for selected physicochemical analysis following standard procedures. The profile was clay loamed at the surface and clayey at the subsurface due to a high content in mineralogical clays. Bulk density (BD) was low in surface and high in-depth, while total porosity had an opposite trend. These soils were generally acidic to slightly acidic, with low pH-values subjecting the soil to exchangeable acidity (EA). Organic matter (OM) content was quite satisfactory, though the alternating wet/dry conditions hindered mineralization. For these reasons, organic carbon (OC) and total nitrogen (TN) stocks were more or less important in some horizons depending on their susceptibility to waterlogging. Phosphorus content was high to moderate in the surface and low at the subsurface. Cationic exchange capacity (CEC_7) rated high, accounting for good potentiality of these soils in terms of fertility. The latter was principally due to smectitic clay minerals as evidenced by the high values of CEC_{-Clay} along the profile. However, mineral fertility was poor as the complex had few nutrients thanks to low pH values that qualified the profile for having an effective CEC (ECEC). The latter were low however and decreased with depth, together with related characteristics such as total exchangeable bases (TEB) and base saturation at ECEC (BS_{-CECE}), thus requiring adequate measures in order to improve the soil's effective holding capacity for nutrients and its sustainability.

Keywords: Wetlands, physicochemical characteristics, hydromorphic soils, Rubiaceae, Cameroon.

INTRODUCTION

The main objective of research in soil science is the understanding of the nature, properties, dynamics and functions of the soil as part of landscapes and ecosystems [1]. Hydromorphic soils are those that are saturated at or near the soil surface with water, and virtually lack free oxygen for significant periods of a given year. They are also referred to as soils affected by redox processes with a particular dynamism of organic matter. Many classification systems, group these soils either under rédoxisols, réductisols, histosols, Planosols or Gleysols, depending on the intensity of hydromorphism. However, the American system of classification (Soil Taxonomy) does not consider hydromorphic soils as a distinct reference soil group, arguing that hydromorphism can affect any type of soil [2]. The occurrence of such soils is usually conditioned by both climate and physiography and the total area which has to do with places where the land's drainage capacity falls short of evacuating the water surplus which may originate from rainfall, surface runoff and ground water flow; thus, they are most prevalent in humid climate and low-lying land [3, 4]. In Cameroon, these soils occur in almost all the agro ecological zones, with the greater part of it being concentrated along the coastal part of the country, flood plains, marshes and alluvial plains [5]. These soils commonly restricted to wetlands serve as refuge to many endemic species of plant with a large percentage being typically infeodated [6]. However, because of demographic pressure, lack of fertile land added to the drop in fertility level of previously cultivated areas, there is an increasing demand for land to intensify agriculture, one of the basic mean of incomes and livelihood of the population in this region. This often results in the conversion of previously abandoned lands such as swamps into farm land after a huge destruction of the natural vegetation may have occurred. Consequently, there is a loss of biodiversity, with hygrophilic plants mostly affected, due to their immobility, their susceptibility to brutal environmental changes and finally their restricted ecological amplitude.

Although many international organisms focus their action on the preservation of such vulnerable ecosystems, much still have to be done in order to couple the level of intervention with the high intensity of anthropogenic activities that continue to negatively affect the ecosystem and wetlands in particular. *Fleroya stipulosa* is one of the outstanding medicinal plant species growing typically on hydromorphic soils as reported by many studies [7, 8, 9, 10, 11]. In Cameroon, though the specie is ubiquitous, their populations seem always to be confined to certain wetlands of their natural range were they constitute the characteristic vegetation, while they escape from others, for reasons not yet elucidated. This species alongside with other members of the genus share similar habitats and have a great history of use as medicinal plant. The latter have been confirmed by many pharmacological studies who advocated their effectiveness in modern and traditional medicine to cure fever, diabetis, malaria, diarrhea, cough, muscular pains, expulsion of worms, infertility, facilitate delivery, manage hypertension and snake bite [12, 13]. The plant extract is very rich in Indole alkaloids among which Mitragynine is reported to have the highest pharmacological activities such as antinociceptive, antinflammatory, anticancer, cardiovascular, antidiarrheal, antibacterial, antioxidant, antidiabetic and hepatoprotective [14-20].

Despite its multiple medicinal values, the species is either vulnerable or at the stage of disappearance because of over exploitation, destruction of its natural habitat, and lack of relevant policies for restoration and conservation strategies [10, 11]. There is therefore an urgent need of protecting the specie both *in situ* in his natural environment or *ex situ* in other environments sharing similar characteristics with the originating site. Prior to these actions, accurate knowledge on site characteristics and edaphic requirement of the species are normally needed, in order to ensure the success and sustainability of the restoration and conservation strategies. Unfortunately many of these actions are found to be ineffective. This is because less emphasis is often granted to edaphic factors since their determination is considered to be very expensive, of marginal interest, scanty or inexistent, thus leading to time, energy and money wastage. However, a basic requirement for a relevant and effective conservation strategy of the species would be the availability of accurate and reliable information on soil characteristics of its realized ecological niche among others. This can only be achieved through proper characterisation of these soils using field observation together with laboratory analysis. It is in order to feel the gap that this study was initiated in other to provide basic data on physicochemical characteristics of soil units under *F. stipulosa*. This would help promote and support a sustainable management of the species in the future.

MATERIALS AND METHODS

The study Area

The study area was in Ntawang, a village of Santchou subdivision, located at 720 m in the Mbo plane, about 20 km away from Dschang city between latitudes 5°10'N - 5°20'N and Longitudes 10°20'E -10°21'E (Figure 1). Santchou lies within the thermic and hyperthemic temperature regimes and has two seasons: a long rainy season, that runs from mid-March to mid-October and a short dry season that spans from mid-October to mid-March. Mean annual temperatures stands at 23.6 °C with March being the hottest month with mean monthly temperatures of 24.8 °C. Mean annual rainfall is 2429 mm, with pick of precipitation occurring between July and September. This area is dominated by *Udic* soil moisture regimes [21]. Mbo plane belongs to the vast Camerounian meridional plateau and constitute the Santchou water basin, with a rich hydrographical network composed mainly of Ménoua, Black water and Nkam rivers [22, 23, 24]. According to [25], the geological history of this plane originated from the Cretace with the breakdown of part of the granito-gneissic socle, leading to a vast depression who was later on closed by lava flows from the Mt Manengouba, giving rise to a lake who was subsequently fitted throughout the years with multiple layers of colluvic and fluviatil materials deposited along the plane by rivers. The main pedogenetic process here is hydromorphism, which expresses some variability according to the location of soil in the toposequence [26]. Thus, ferralitic soils occur at the peripheral zones located at high altitude, while humic soils are found in medium altitude under the forest cover, and finally hydromorphic soils occupy the marshes and low-land areas corresponding to Menoua, Black water and Nkam valley. They are either exondated, floodable or flooded either permanently or temporally with a characteristic vegetation cover, including species such as *Gnetum africanum*, *Prunus africana* and *Voacanga africana* occupying the ferralitic soils [24, 25, 27]. In the medium levels are shrub savannas or degraded forest with *Pennisetum purpureum*, *Albizia gummifera*, *Vitex* sp. and *Triumfeta cordifolia* as typical species. Hydromorphic soils are characterised by monocotyledons such as *Hyparrhenia rufa, Phoenix reclinata, Thaumatococcus daniellii (Benn.) Benth* and *Raphia vinifera.* Dicotyledons such as *Fleroya stipulosa*, *Anthocleista microphylla*, *Alchornea cordifolia* and *Uapaca guineense* are also very characteristic. The population is mainly from Mbo and Bamiléké tribes followed by Bamoun and Anglophones from Nord West and South West Regions. Their main activity is agriculture with coffee, cocoa and palm trees as main crops, alongside with cash crops such as sweet potato, plantain, cassava and okro [27]. For agricultural purposes they have gradually destroyed large natural stands of *F. stipulosa* in some wetlands and

neighbouring environments. This could be acknowledged on the field by the presence of few solitary members of the specie, scattered within many

farms. Fishery, hunting, pisciculture and sand exploitation in the river Menoua are also part of the daily activities that generates large incomes to the people.
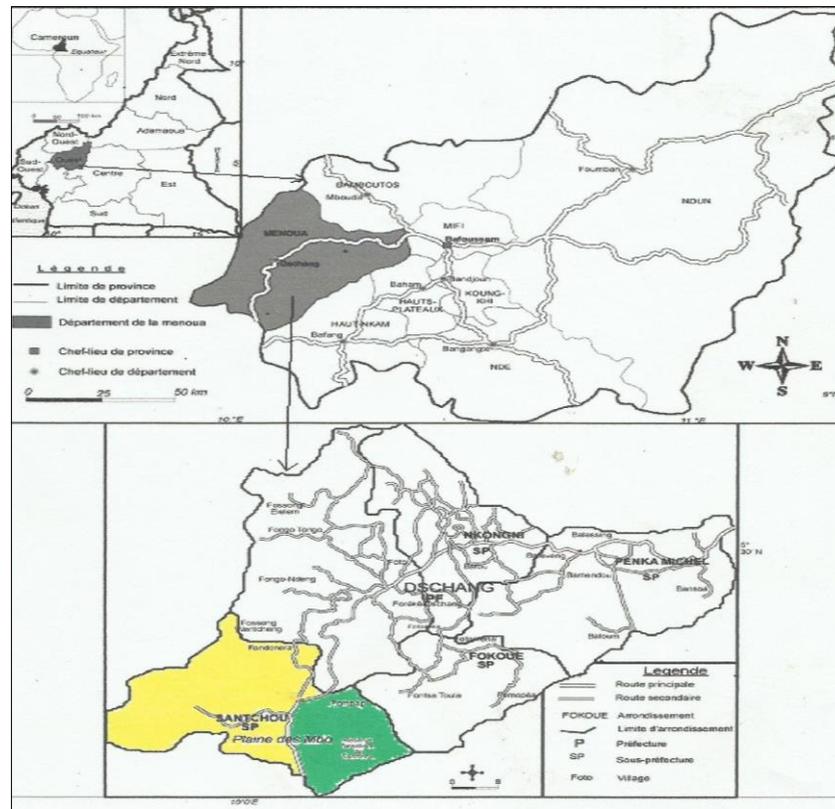
Fig-1: Map of Cameroon showing Santchou subdivision

Soil sampling and field analysis

A fresh representative soil profile pit with 1m width, 2m length and 2.5 m depth , located in the middle of a pure natural stand of *F. stipulosa* vegetation at 05° 18' 25.9''N and 9° 58 49.0''E, was excavated. The soil profile was then described morphologically under field condition according to [1] manual and sampled depth-wise (layers) from bottom to surface layers, for characterization of some selected physicochemical properties. Undisturbed (bulk) samples were taken with core samplers of known volume (100 cm^{-3}), while disturbed samples were collected using a trowel from each horizon. They were then put into polythene bags whit special references and brought to the Laboratory of Environmental and Analytical Chemistry of the University of Dschang, where routine analysis took place.

Laboratory analysis

In the laboratory, both disturbed and undisturbed samples were analysed, following standard procedures outlined by [28]. Undisturbed core samples were used for the determination of some selected physical properties such as bulk density (BD), total porosity (P) and soil solid space. Bulk density was determined by weighing soil cores after drying at 105ºC till constant weight. Mass of solid particles was obtained

by weighing solid particles and likewise volume from mass and density of water displaced by soil samples. The total porosity (P) was calculated from the bulk densities (BD) and soil particle densities (PD) using de relationship outlined by [5]: P (%) = 100 (1 - BD/ PD), with PD = 2.65g.cm^{-3}. Disturbed soil samples were used for the determination of other physical and chemical properties after air and oven-drying, gently crushing in a porcelain mortar and sieving to 2 mm through a mesh. The fine fraction (<2 mm) was then used for the determination of parameters such as: texture, pH, electrical conductivity (EC), organic carbon (OC), organic matter (OM), total nitrogen (TN), available phosphorus, cation exchange capacity (CEC), exchangeable bases (Ca^{2+}, Mg^{2+}, Na$^+$, K$^+$), total exchangeable bases (TEB) and exchangeable acidity (EA). Particle size distribution was determined by the hydrometer method after dispersion of samples with 5% sodium hexametaphosphate. Textural classes were determined using the textural class triangle [29]. Soil pH was measured in 1: 2.5 soil to solution ratio in 1N KCl (pH-KCl) and distilled water (pH-H$_2$0) using a glass electrode pH meter. The electrical conductivity was measured at 25°C by immersing a WTW model conductimeter in the filtrate obtained after stirring a mixture of 10 g of air-dried soil and 50 ml of distilled water. The soil/water extraction ratio was 1:5. Organic

carbon (OC) content of the soil was determined by the wet oxidation method and titration with ferrous sulfate [30]. Organic carbon values obtained were then converted to organic matter (OM) by multiplying by a factor of 1.724 [31, 32]. Total nitrogen (TN) was determined using the micro-Kjeldalhl digestion-distillation method followed by titration with chlorhydric acid as described by [33]. Available phosphorus (AP) was determined using filtrates extracted by the Bray II method and quantified with a molecular absorption spectrophotometer (MAS) at 665 nm wavelength following colour developed by the molybdenum blue [34]. Apparent CEC (CEC_{-soil} or CEC_7) were determined after saturating 2.5g of soil with 100 ml of neutral 1M NH4OAc (ammonium acetate), removing the excess with ethanol and displacing the adsorbed NH_4^+ using 1M KCl, followed by Kjeldalhl distillation and titration with 0.01 N sulfuric acid [35]. Exchangeable bases (calcium, magnesium, potassium and sodium) in the soil were determined using the ammonium acetate extract from the CEC determination. Potassium (K) and sodium (Na) were determined using a flame spectrophotometer while magnesium (Mg) and calcium (Ca) were determined by complexiometric titration using EDTA (Ethylen-diamine-tetra acetic acid). Total exchangeable bases (TEB) were calculated as sum of exchangeable bases Ca^{2+}, Mg^{2+}, K^+ and Na^+. Exchangeable acidity (EA) was determined by leaching the soil with 1N KCl in the ratio 1:20, followed by titration with 0.05 N NaOH [28]. Effective cation exchange capacity (ECEC) was determined as sum of bases and exchanged acidity (EA). Base saturation at CEC_7 (BS_{-CEC7}) and at ECEC (BS_{-ECEC}) were determined using the formula outlined by Yerima and Van Ranst [5]: BS_{-CEC7} (%) = TEB x 100 /CEC; BS_{-ECEC} (%) = TEB x100/ECEC. To access the clay mineralogy, the cation exchange capacity of the clay fraction (CEC_{-clay}) was also derived from the relation outlined by [35] as: CEC_{-clay} = {[CEC_{-soil} - 3,448 %C]/ (% clay)}* 100. The contribution of OM to soil's CEC (CEC_{-sof}) was also calculated using the formula: CEC_{-sof} = 1.724 *2* %OC.

Data processing and statistical analysis

Laboratory data were computed and processed using Microsoft Excel 2007, then subjected to descriptive statistics using XlStat statistical software. The discussion of the results was made on the basis of available standards on the assessment of physicochemical status of soils [36- 42]. In other words, the results of the soil analysis were compared with established ratings and/or critical levels or limits for different classes of the respective plant nutrient elements in evaluating the fertility status of the soils studied.

RESULTS AND DISCUSSION
Physical characteristics

The results of the physical characteristics of a representative soil profile under *F. stipulosa* stands in the Mbo plain are summarized in Table 1 and Table 2. The clay content increased with depth from 42 % to 68 % while silt and sand decreased from 42 % to 26 % and 16 to 6% respectively. The clay and loam fractions dominated the soil's fine fraction, with cumulative values of 84 %, 96 % and 94 % in Apg, ABg and Bwg horizons respectively. Because of this high content of clay and silt in all the horizons, the average textural class of the profile was silty clay and could be evidence analytically by a high retention capacity for water and nutrients together with a high cation exchange capacity (CEC) of the soil. Apparently, particle size distribution has important bearing in soil water movement, aeration, root extension, oxidation-reduction processes and nutrient and OM contents as well as composition [43]. Such textures would be likely to hinder root penetration, prevent water from draining freely and confer these soils a high retention capacity to water and nutrients [5, 44, 45]. This is because clay has good colloidal properties and very high surface areas that give nutrients numerous binding places as well as small pores space between particles that hinder the percolation of water and circulation of gases [5, 46]. A coupling between the different textural classes observed in the soils of the Mbo plain and the CEC of the clay fraction (CEC-clay) corresponding to each horizon of the pedological profile confirms this trend, the values of CEC-clay being between 42, 24 and 72.67 cmol (+) / kg of soil. The high value of CEC-clay horizons ranked the profile within "high activity clay soils" category [5]. Gray soils with similar properties have been identified and described in the hydromorphic lowlands of a colluvio-alluvial smectitic mineral cover in Ivory Coast [47]. According to [48], such soils with high percentage of clay and silt are recommended for agricultural practices as they are capable of providing good aeration and retention and therefore supply nutrients and water. These soils were rich in such parameters, thus predicting high agronomic potentials. But, unlike texture, a relatively stable physical feature, the structure of the horizons were dynamic as they responded to mechanical constraints imposed to them by abiotic (rainfall, temperature) and biotic (root system, soil fauna) factors. Generally angular to subangular blocky during dry season, the structure became massive and compact with rainy season, thus conferring the soil a prolonged resistance to root penetration. Moreover, with the confined environment associated to poor, imperfect or limited drainage, the dissolved mineral elements are very little evacuated, hence leading to a relatively high concentration of the soil in some exchangeable cations and in neoformed or inherited clay minerals of smectitic type.

Table-1: Analytical data of selected physical properties of the studied soil profile under *F. stipulosa*.

	Oapg	Apg	ABg	Bwg
Soil depth (cm)	0-2	2-9	9-32	32-250[+]
Silt (%)	-	42	32	26
Sand (%)	-	16	4	6
Clay (%)	-	42	64	68
Textural class	-	CL	C	C
Bulk density (g.cm^{-3})	-	1.75	1.96	2.09
Total porosity (P %)	-	33.96	26.04	21.13
Solid space (%)	-	66.04	73.96	78.87

Table-2: Descriptive statistics of selected physical characteristics of the studied soil profile under *F. stipulosa*

Soil properties (n=3)	silt	Sand	Clay	BD	Porosity	Solid space
Mean	33,33	8,67	58,00	1.93	27.04	72.96
MSE	4,67	3,71	8,08	0.10	3.74	3.74
St.Dev.	8,08	6,43	14,00	0.09	6.47	6.47
Variance	65,33	41,33	196,00	0.03	0.24	41.91
Minimum	26,00	4,00	42,00	1.75	21.13	66.04
Maximum	42,00	16,00	68,00	2.09	33.96	78.87
CV (%)	24	74	24	5	24	9

MSE= Mean standard error; **St.Dev.** = standard deviation; **CV**= coefficient of variation; **BD**: Bulk density.

Bulk density (BD) is one of the most important parameters in studies of soil physical characteristics. It is related to the nature and organization of the soil constituents and takes into account the gaps that exist between the solid phases [49, 50]. At the field capacity, the water content is mainly related to the structural porosity, itself in relation to tillage, biological activity and texture. Bulk density appears as a very good indicator of the water retention capacity of a soil. The Bulk density (BD) of the profile was lower at the surface, but increased with depth from 1.75 g.cm^{-3} in Apg horizon to 2.09 g.cm^{-3} in Bwg, with a mean value of 1.93g.cm^{-3}. According to [51], A-horizons of cultivated soils normally have BD ranging from 0.9 to 1.8 g.cm^{-3}, with values below this range characterising organic layers or volcanic ash. Bulk density is influenced by the organic matter content, the texture, mineralogy, and porosity [52]. The high BD recorded in the subsurface horizon may have resulted from a lower organic matter content, a lesser aggregation between soil particles and compaction caused by the weight of the overlying layers. The overall high BD values suggested that the soils were compact, making root penetration and free diffusion of water and air through the soil difficult. A similar observation was made in Tanzanian soils [53]. According to [5], clayey soils with a BD > 1.55 g.cm^{-3} are unfavorable to root penetration because of their compactness. The normal range of bulk densities for clayed soils is between 1.0 and 1.6 g.cm^{-3} with potential root restriction for BD ≥ 1.4 g.cm^{-3}[54, 55]. Root growth could therefore be inhibited in Ntawang series, because of high BD and the related soil resistance to root penetration, poor aeration, slow movement of nutrients and water and build-up of toxic gases and root exudates

[56, 57]. Consequently, the relatively low BD value of Apg horizon could be more favourable for root development compared to the underlying layers that would impair proper root penetration. The antagonistic effect of such high BD on the species rooting was evidenced *in situ* by a pronounced development of the root system in surface horizons compared to the subsurface.

The porosity (P) represents the volume occupied by the pores of the soil relative to the solid phase. It depends on BD and the density of the solid particles. Soil fertility is better when there is no excessive variation of its porosity as a function of humidity [58]. The mean porosity of the profile was 27.04%, but showed a clear variation between the layers. It was high in surface in Apg (P = 33.96%), but decreased gradually in ABg (P = 26.04%) up to a minimum value in Bwg (P = 21.13%). A total porosity less than 30% is rated as poor, the best being those greater than 50% [59]. Pore sizes below 40% and described as low were obtained by [4] in some hydric soils of the Niger-delta of Nigeria. According to [21], soils associated with low porosity and fine texture seriously hinder plants growth, because of their more or less asphyxiating nature. In addition, the more a soil is rich in organic matter, its texture fine (<2μm) and its adsorbent complex rich in flocculent ions (Ca^{2+}, Mg^{2+}), the more it tends to have a low BD as well as a high porosity. The low BD recorded in the Apg- horizon compared to the underlying horizons could be linked not only to its richness in fine particles and organic matter, but also to the rhizosphere effect which, coupled with the high activity of the microfauna, contributed in increasing

the voids between aggregates, and to lower the BD [5, 45]. On the other hand, BD and compactness increased with depth while porosity and aggregation of particles decreased because of the weight of overlying horizons, the low organic matter content associated to a low rhizosphere effect and limited biological activities. Similar observations were made in some hydromorphic soils in Nigeria [4, 60, 61].

Chemical characteristics

Chemical properties and descriptive statistics of physicochemical parameters of soil horizons from the studied profile are presented in Table 3 and Table 4 respectively.

Table-3: Chemical characteristics of soil under *Fleroya stipulosa* in Ntawang

Soil horizons	Oapg	Apg	ABg	Bwg
depht (cm)	0-2	2-9	9-32	32-250+
Soil reaction				
pH-$_{H2O}$	6.2	5.2	5.3	5.2
pH-$_{KCl}$	4.9	4.1	4.3	4.3
ΔpH	-1.3	-1.1	-1.0	-0.9
EC (dS.cm^{-1})	0.02	0.49	0.18	0.04
Organic matter				
OM (%)	0.81	9.94	4.16	2.84
OC (%)	0.46	5.16	2.41	1.65
TN (%)	0.31	0.23	0.15	0.19
OC (%)	0.47	5.76	2.41	1.65
C/N	1.50	24.76	15.80	8.55
Exchangeable bases (cmol(+)/kg)				
Ca^{2+}	6.64	1.76	2.12	0.64
Mg^{2+}	1.24	0.24	0.44	0.36
K$^+$	0.50	0.43	0.58	0.43
Na$^+$	0.17	0.17	0.17	0.17
TEB	8.55	2.60	3.31	1.60
EA (cmol(+)/kg)	-	0.28	0.06	0.073
Cation exchange capacity (cmol(+)/Kg)				
CEC$_7$	77.2	50.4	36.96	34.4
ECEC	8.55	2.87	3.37	1.67
CEC-Sof	-	19.87	8.31	5.67
CEC-Cco	-	72.67	44.76	42.24
Base saturation (%)				
BS-$_{CEC7}$	11.077	5.15	8.94	4.64
BS-$_{ECEC}$	-	90.35	98.11	95.64
Avail. P (mg/Kg)	65.65	20.60	7.51	5.44

ESP: Exchangeable sodium percentage; **BS**: Base saturation; **CEC$_7$**: Cationic exchange Capacity at pH7; **ECEC**: effective cationic exchange capacity; **TEB**: Total exchangeable bases; **EA**: Exchangeable acidity; **CEC-sof:** CEC of soil's organic fraction; **TN**: Total Nitrogen; **CEC-Cco**: CEC-clay (corrected); **OC**: organic carbon; **OM**: Organic matter; **EC**: electrical conductivity; Δ**pH**= pH-$_{Kcl}$ - pH-$_{H20}$.

Soil pH, along with moisture content, limestone and sodium chloride, are edaphic factors that create the greatest large-scale discrimination in plant distribution [45]. The majority of them having a harmonious development in soils with pH values ranging from 6 to 7.5 [37, 42]. The soil reaction of the profile according to [62] was generally acidic as the pH-H$_2$0 varied from acid to slightly acid (5.2 - 6.2) and pH-KCl, though variable remained acid (4.1 to 4.9). The acidic nature of the

profile could be attributed to the redox products of ferrolysis that is common in wetland soils [4]. The variation of pH (ΔpH) was negative throughout the horizons, indicating that the net charge balance on the adsorbent complex was negative, and thus exhibited a cation exchange capacity (CEC). Similar trend was observed by [63] in wetland gardens of Bamenda in Cameroon. Apart from the Oapg-horizon, both surface and subsurface horizons exhibited an exchangeable

acidity (EA), due to their low pH (<5.5), very favorable for the passage of aluminum to exchangeable forms [64]. The EA varied from 0.06 to 0.28 cmol(+)/kg between ABg and Apg horizons respectively. According to [40, 64], at low pH values, many detrimental phenomena to plants growth occur in soils, including reduced nitrification, phosphorus deficiency, aluminum and manganic toxicity, low mobility of organic pollutants

and high availability of some heavy metals. Addition of $CaCO_3$ in these soils could be beneficial as it would rise up the pH and prevent harmful reactions to occur. The electrical conductivity ($CE_{1/5}$) was low and varied from 0.02 to 0.49 dS.m^{-1}, with a mean value of 0.18 dS.m^{-1} between horizons indicating that these soils had no problem of salinity [65].

Table-4: Descriptive statistics of chemical properties in a representative soil profile under *F. stipulosa*.

Properties	Obsv.	Min	Max	Mean	Std.Dev.	Variance	CV (%)	SEM
pH-H$_2$0	4	5.20	6.20	5.48	0.42	0.18	7.66	0.24
pH-KCl	4	4.10	4.90	4.40	0.30	0.09	68,1	0.17
ΔpH	4	-1.30	-0.90	-1.08	0.15	0.02	13.89	0.09
EC(ms.cm-1)	4	0.02	0.49	0.18	0.19	0.04	103	0.11
OM (%)	4	0.81	9.94	4.44	3.39	11.51	76	1.96
TN (%)	4	0.15	0.31	0.22	0.06	0.004	27	0.03
OC (%)	4	0.47	5.76	2.57	1.97	3.87	76	1.14
C/N	4	1.50	24.77	12.67	8.63	74.51	68	4.98
Avail. P (mg.kg^{-1})	4	5.44	65.65	24.80	24.29	590.06	98	14.02
Ca^{2+} (cmol(+)/kg)	4	0.64	6.64	2.79	2.29	5.24	82	1.32
Mg^{2+} (cmol(+)/kg)	4	0.24	1.24	0.57	0.39	0.15	69	0.23
K$^+$ (cmol(+)/kg)	4	0.43	0.58	0.48	0.06	0.004	13	0.04
Na$^+$ (cmol(+)/kg)	4	0.17	0.17	0.17	0.00	0.00	0.00	0.00
EA (cmol(+)/kg)	3	0.06	0.28	0.14	0.10	0.01	72	0.07
TEB (cmol(+)/kg)	4	1.60	8.55	4.01	2.69	7.24	67	1.55
CEC$_7$ (cmol(+)/kg)	4	34.40	77.20	49.74	16.98	288.28	34	9.80
ECEC (cmol(+)/kg)	4	1.67	8.55	4.12	2.63	6.94	64	1.52
CEC-clay(cmol(+)/kg)	3	50.59	120.00	76.11	31.17	971.59	41	22.04
CEC-sof (cmol(+)/kg)	3	5.68	19.88	11.29	6.17	38.02	55	4.36
CEC-Cco (cmol(+)/kg)	3	42.24	72.67	53.22	13.79	190.25	26	9.75
BS-$_{CEC7}$(%)	4	4.64	11.08	7.45	2.67	7.14	36	1.54
BS-$_{ECEC}$ (%)	4	90.35	100.00	96.03	3.62	13.12	4	2.09

Std. Dev. : Standard deviation; **SEM:** standard error of means; **CV:** coefficient of variation; **BS:** Base saturation; **CEC$_7$:** Cationic exchange Capacity at pH7; **ECEC:** effective cationic exchange capacity; **TEB:** Total exchangeable bases; **EA:** Exchangeable acidity; **CEC-sof:** CEC of soil's organic fraction; **TN:** Total Nitrogen; **CEC-Cco:** CEC-clay (corrected); **OC:** organic carbon; **OM:** Organic matter; **EC:** electrical conductivity; **ΔpH**= pH-$_{Kcl}$ - pH-$_{H20}$.

The organic matter (OM) contents were found to concentrate more in the Apg-horizons and decreased with profile depth. These OM contents, according to critical values by [38] varied from very low to very high with a range from 0.81 to 9.94% between Oapg and Apg respectively. Since their evolution in soils is closely related, Organic carbon (OC) content followed the same trend as OM and ranged from 0.46 % to 5.16 % between Oapg and Apg horizons. For a given soil to be considered rich in organic matter, its content must be greater than 2%. The high OM and OC contents in Apg could be ascribed to continuous litter supply of the soil surface associated with a slow decomposition rate of OM caused by excess water, which significantly influences pedogenesis in Mbo plain [25, 27, 32]. This water depletes the soil from oxygen and creates favorable conditions for strict anaerobic microorganism's

activities at the expense of aerobic microorganisms, the latter being involved in proper mineralization process of OM as it is the case in Oapg horizon [66]. In these more or less anoxic conditions, strict anaerobes would cause a slow degradation of carbohydrates and proteins contained in the OM, leading to their accumulation in less biodegraded form in the profile [32]. The low OM and OC contents in Oapg could be linked with good oxygen supply of this part of the soil. Under such conditions, humification is rapid and results in a complete mineralization of OM with the release of carbon in the form of CO_2 into the atmosphere, hence, lowering the total OC content recorded in the Oapg horizon. With depth however, as water occupied the total porosity, oxygen decreased, and aerobic bacteria give place gradually to facultative, and finally, strict anaerobic microorganisms more involved in putrefaction

processes of the OM that accumulates more or less in the profile together with OC.

The total nitrogen (TN) content followed the same trend with OC and OM as it decreased with depth and the nature of the soil horizons, with however a slight rise in the illuvial horizon B_{wg}. These levels found between 0.15 and 0.31% with a CV of 19% varied, according to [38] from moderate to very high in ABg and O_{apg}-horizons respectively. The moderately to very high TN contents in ABg and Oapg horizons could be associated with a good mineralization of OM accumulated at the soil surface thanks to nitrous (Nitrosomonas *sp*.) and nitric (Nitrobacter *sp*.) bacteria [5, 67]. To these biological sources of nitrogen, the contribution of ammonia fertilizers (urea, ammonium sulphate and ammonium nitrate) to the TN content of the soil is not to be neglected, as they are commonly used by farmers of this agroecological zone to improve their productivity. With depth however, and because of the more or less permanent water table combined with high rainfall, (2429mm / year in Ntawang), incomplete mineralization of OM occurs, as microbial activities becomes limited. As a result, NH_4^+ produced accumulates and later on oxidises into to nitrite (NO_2^-) and nitrate (NO_3^-), as the water table gradually moves down the profile during dry season [21]. But the rapid return of rainfalls and complete saturation of subsurface and part of surface horizons by ground and running water create reducing conditions and favour denitrification of the soil mostly through leaching and anaerobic microorganism's activities. The overall result of these cyclic redox processes occurring in such hydromorphic soils is a clear accumulation of nitrogen in the profile, both in the form of complex organic substances, NH_4^+, N_2, NO_2^- and NO_3^-.

The C/N ratio gives an idea of the degree of evolution and the quality of organic matter in the soil as well as the quantity of nitrogen available for plant nutrition. This ratio ranged between 1.50 and 24.77 with a CV of 68%, indicating that the degree of evolution and the quality of OM was variable between the horizons. According to [37], the OM was very well evolved and of good quality in Oapg (C/N=1.5) and Bwg (C/N=8.55). It was poorly evolved and of poor quality in ABg (C/N=15.80), but less evolved and of very poor quality in Apg (C/N=24.77). The good C/N ratio of the Oapg horizon accounted for a good biological activity in the soil, resulting in a complete mineralization of OM and good nitrogen feeding opportunities [68]. The very high C/N (> 20) in Apg (C/N = 24.76) indicated an OM of very poor quality due to very low biological activity as the horizon was more subjected to water table because of the impermeable character of the underlying horizons. The very high C/N ratio in Apg also accounted for a limited humification process as it stops at the ammonification stage under anaerobiosis [5, 69]. As a result of this incomplete reaction, NH_3 could be adsorbed

on the complex in the form of NH_4^+ and hence the potentialities for a good nitrogen supply in this horizon could be restricted to the ammoniacal form instead of nitrate (NO_3^-) as it is for the majority of plants. According to Duchaufour [44], the type of humus characteristic of such very high C/N ratio (24.76) was moder (18 < C / N <25).

Phosphorus is the second most important macronutrient available in biological systems, which accounts for more than 1% of the dry organic weight [56]. It is absorbed by plants in the form of phosphate ions ($H_2PO_4^-$, HPO_4^{2-}). It is generally present in tropical soils in smaller amounts than nitrogen, but their synergistic action promotes the growth and good development of plants. As growth factor, it stimulates root development and the abundance of flowering and fruiting [58]. Phosphorus also plays a decisive role in the constitution of many structural elements essential to cell's life (phospholipids, nucleic acids), in energy exchanges and in many metabolic reactions [48]. In soil units under *F. stipulosa* , available phosphorus levels decreased with an increasing depth of the profile, the recorded values ranging from very low (5.44 mg.kg^{-1}) in Bwg to high (65.65 mg.kg^{-1}) in Oapg with a CV = 98% between the horizons [37]. Subsurface horizons were therefore poor in phosphorus as compared to surface horizons that were rich. An available phosphorus level of 15mg.kg^{-1} is generally considered to be the critical threshold below which a soil is considered to have a low content in phosphorus, leading to deficiency diseases in most plants [40]. A similar trend was noted by [70] on Haplic Cutanic Acrisols/ Typic Haplustults in Kenya. In tropical areas, the annual production of litter is important, but varies according to the vegetation type and the phenological behavior of the species which compose it [71]. This litter is the main source of soil biochemical elements such as phosphorus, particularly in the tropics and subtropics where parent minerals rich in phosphorus are rare or nonexistent [72, 73, 74].The high content of phosphorus found in part of the surface horizons (Oapg and Apg) could therefore be associated to OM that was present in the form of more or less decomposed litter from the abscised leaves of *F. stipulosa* on the soil surface, the species being deciduous [75]. The high phosphorus content of the surface horizons could also be linked to human activities in the Mbo Plain, including inputs in the form of organic manure, agricultural residues (coffee pulp) and phosphate fertilizers, which would result in an increase in phosphorus concentration of the surface horizons. The low phosphorus content in the subsurface could partly result from the abundant drainage and leaching, but more from the strong adsorption (chelation) of phosphates ions by the iron and aluminum oxides very abundant in tropical soils with acidic pH as it was the case in this study [76]. But, the availability of phosphorus could also be limited due to the granitic nature of the parent material, and also because phosphorus is poorly retained

on the soil complex [5]. Similarly low phosphorus content was reported in many soils with aquic moisture regime in some wetlands of Nigeria [61, 77].

The set of negative charges in a particular soil is its cation exchange capacity (CEC). This indicator represents the ability of the soil solid phase to retain and release up to the soil solution, some cations especially those directly involved in plant nutrition [78]. The CEC, which is actually a functional property of the soil, illustrates both its function as a pantry for plants and a reservoir that buffers the osmotic pressure between the external environment and root cells. The CEC of soils is due principally to mineralogical clays and humic compounds, but also varies with texture, OM content and the mineralogical composition of the soil. The CEC measured at pH = 7.0 (CEC_7) of the profile was high though it decreased with depth, from very high (77.20 cmol(+)/kg) in Oapg to high (34.40 cmol+/kg) on the scale of [32]. This gives a strong adsorbing power to the entire profile. Similar CEC ranges but varying between 30 and 80 cmol(+)/kg of dry soil were recorded by [21] in Vertisols of North Cameroon. The high CEC_7 values recorded in the profile could result mainly from the nature of mineral clays, and OM to a certain extent [79]. But in these soils, the contribution of the clay fraction to the fertility of the soil is greater than that of the organic fraction. Typically high values of CEC-clay recorded in the Apg, ABg and Bwg horizons, ie 72.67, 44.76 and 42.24 cmol(+)/kg respectively were suggestive of the types of clay minerals present in this soil. These would probably be smectites (montmorillonites), known to be very common in high activity rich clay soils, interbedded with chlorites, illites and micas. These smectites are frequently formed in confined environments during the alteration of parent rocks, where drainage is poor enough to retain certain cations such as Mg^{2+} and Fe^{2+}. The geomorphology of the Mbo Plain (large depressional basin) together with the ecoclimatic characteristics of the station (wet seasons alternating with periods of strong desiccation) led to this neosynthesis of smectitic clays of 2:1 type. The latter's presence could be evidenced through deep wide cracks opened up in an irregular but somewhat polygonal pattern, observable on the soil surface and throughout the profile, as a result of dehydration occurring during dry season [5]. These cracks disappeared temporarily during rainy season following swelling of the clays minerals, the water balance of the soil becoming positive because of a decrease of its permeability. The more or less variable OM content and exchangeable bases in the profile could also result from the frequent pedoturbation which alternately raised or lowered material coming from the surface. Because of the abundance of the clay fraction (58% on average), the predominance of smectitic minerals, a very high CEC_7 in the horizons (34.40 - 77.20 cmol (+) / kg), a high CEC-clay (42.24 -72.67 cmol (+) / kg) and of the shrinkage / swelling character of the clays, the soils under *F. stipulosa* vegetation converged strongly to vertisols. However mineralogical analysis and detail morphological characterisation of the profile would help in increasing the accuracy of this hypothesis.

Although it had a good adsorbent capacity, the mineral fertility of soils under *F. stipulosa* was poor, as evidenced by the low nutrient content (exchangeable bases) actually fixed on the complex. They were represented in the Oapg-horizon by Ca^{2+}, Mg^{2+}, K^+ and Na^+, to which Al^{3+} and H^+ were associated in the underlying horizons because of their acidic nature (pH <5.5), very favorable for the passage of aluminum from its insoluble form $Al(OH)_3$ to soluble forms.

Calcium and Magnesium are two important elements of the soil, not only because many of the characters and properties of the soil depend on their content, but also because they are indispensable for proper development of microorganisms and vegetation [80]. Magnesium is absorbed by the roots in the form of Mg^{2+} and plays a major role in the production of energy in plants. It is a component, together with nitrogen of the chlorophyll present in all plants. Magnesium is also an activator of metabolic enzymes as it is involved in the translocation and synthesis of proteins. Calcium on his part is an essential nutrient for plants and it is absorbed as Ca^{2+} by the roots. Its main functions are: to participate in the constitution of plant cell walls by stiffening them; activate various enzymes including nitrate reductase to reduce ammonium nitrate in the leaves and promote the growth of young roots in synergy with other elements [69]. Potassium is a nutrient taken in large quantities by the plant as K^+. It helps to maintain plant turgor and regulates the synthesis, transfer and accumulation of assimilates in reserve organs. It intervenes in the closing and opening of plant stomata by regulating osmotic pressure. In addition, potassium activates various enzymes and increases plant resistance against fungal diseases [45].

Calcium and magnesium dominated the complex of the upper part of the surface horizon (Oapg), with respective contents of 6.64 and 1.24 cmol (+)/kg. With increasing depth, the situation became reversed in the underlying horizons where Ca^{2+}, though still predominant ranged from very low (0.64 cmol+/kg) to low (2.12 cmol+/kg) in Bwg and ABg respectively [37]. They were followed in order of decreasing content by K^+ (0.50 cmol+/kg) and Na^+ (0.17 $cmol^+$/kg). In general, the order of magnitude of exchangeable cations on the adsorbent complex of most tropical soils follows the trend $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ [21, 81]. A similar trend was observed by [82] on some Vertisols and Vertic Inceptisols in the Bale region of Ethiopia, though with higher Ca^{2+} and Mg^{2+} levels than those of the present study.

Apart from the Oapg-horizon where calcium content (Ca^{2+} = 6.64 cmol+/kg) was moderate, the underlying horizons globally had low content in Calcium, despite a slight rise in ABg-horizon. The moderately high content in Ca of the upper part of the surface layer could result from the in-depth uptake of exchangeable bases by trees root system and their redistribution at the surface through litters fallout, otherwise known to be highly rich in biogenic elements, with calcium (184 Kg /ha) constituting the higher content in tropical rainforests [69, 67, 71, 72]. The low Ca content in underlying horizons were normal according to [40] because at pH $\leq$ 5.5 there is an excessive occupation of the complex by H^+ and Al^{3+} ions, resulting in the displacement of exchangeable bases and their lixiviation from the soil by the percolating water. This could also be a result of the close relationship linking Ca content and soil pH and acidity, the latter being higher when Ca^{2+} is less abundant and vice-versa [40, 69, 83]. In acidic hydromorphic environment, the reduced biological activity often leads to a low release of exchangeable bases from the OM. Thus Calcium deficiencies could also be normal because of the greater absorption rate of this element compared to its release rate from various sources present in the soil [40].

Calcium was followed on the complex by K^+, the contents of which was average and ranged from 0.43 cmol(+)/kg in Apg and Bwg to 0.58 cmol (+)/kg in Bwg, closely followed by Mg^{2+}, whose contents ranked low as they ranged from 0.24cmol(+)/kg in Apg to 0.44 cmol(+)/kg in ABg, and finally Na^+(0.17 cmol+/kg) whose content ranked very low in all the horizons [37]. According to [5], 95-99% of the potassium present in the soil is found in primary minerals rich in potassium (feldspars, micas) as well as in the interfoliar space of mineralogical clays (smectites, illites). The globally clayed texture of the profile alongside with the possible presence of smectitic clay minerals in this granite dominant geopedological basin could corroborate the moderately high K^+ contents obtained in the profile.

In the tropics, the Mg^{2+} deficiency threshold is set at 0.5 cmol (+)/kg [84]. All horizons of the profile had Mg^{2+} levels below this critical threshold, probably as a result of depletion caused by percolating water and anthropogenic activities such as agriculture, bushfire, exportation trough post-harvest activities and deforestation. The low contents in Na^+ indicated that the soil had no problem of sodicity or salinity. This could be due to high Na^+ solubility and mobility, which facilitate their leaching out of the profile thus reducing their concentration in the soil.

Total exchangeable bases (TEB) of the profile decreased overall with depth, from 8.55 cmol (+)/kg to 1.60 cmol (+)/kg. The TEB was very low (<2) in Bwg (1.60 cmol+/kg), low in Apg (2.60 cmol+/kg) and ABg

(3.31 cmol+/kg), but moderate in Oapg (8.55 cmol+/kg) according to [38]. The surface horizon was somewhat enriched in bases compared to the underlying horizons because of the dominating Ca^{2+}. Soils with similar characteristics have been described in Tanzania [85]. This could be attributable to trees root systems that draw huge quantity of mineral elements from subsoil and incorporates them into their aerial tissues through photosynthesis before returning them back to upper part of the soil as OM [67, 86, 87]. As a result of this biogeochemical cycle, deep horizons are constantly depleted from nutrients in favor of surface horizons, leading to a gradual desaturation of the exchange complex and a low fertility status of subsoils under *F. stipulosa* in Ntawang. Increased leaching of these nutrients, associated with low pH and a low rate of humification of OM in these hydromorphic pedoclimax could also justify this situation. Hence, the chemical fertility of the profile was limited at the surface and was largely dependent on the stocks of mineral elements contained in OM and plant biomass.

The effective cation exchange capacity (ECEC), or CEC at soil pH, is the sum of cations attached to the adsorbent complex of the horizon considered under natural conditions. The overall ECEC of the horizons were always less than 10 cmol$^+$/kg as they ranged from very low (1.67cmol$^+$/kg) to low (8.55 cmol$^+$/kg) in subsurface and surface horizons respectively, with a very low mean content of 4.11 cmol(+)/kg for the entire profile. Values of ECEC close to 4 cmol (+)/kg are considered as the limit threshold below which soils are considered to be poor in nutrients [84, 88]. It would be imperative to adopt sustainable practices that would raise-up soil pH close to neutrality in order to enhance the retention capacity and thus prevent leaching losses of nutrients, particularly exchangeable bases [88]. A rapprochement between the ECEC and CEC_7 showed that ECEC < CEC_7 in all horizons, thus indicating that the adsorption of charges on the complex was pH-dependent, a drop in pH (<5.5) resulting in a stronger fixation of H^+ and Al^{3+} ions on the complex, to the expense of exchangeable bases that passed in solution thus leading to a low ECEC [5, 69, 89]. Thus, by adjusting the pH to neutrality during the analysis of these strongly altered and clay-rich soil samples, the complex developed more negative charges, explaining the superiority of CEC_7 on the ECEC [88] Therefore, it would be advisable under these conditions, to take into account the ECEC since CEC_7 overestimates the real value of the soil nutrient load.

The base saturation rate (BS) of the complex is a valuable pedological and agronomic indicator of soil chemical richness [69]. The BS of soils varies depending whether CECE (BS-$_{CECE}$) or CEC (BS-$_{CEC7}$) is taken into consideration. But only the base saturation that takes into account the ECEC (BS-$_{ECEC}$) accounts for the current state of the adsorbent complex [90]. At CEC_7, all the

horizons were depleted of nutrients, as evidenced by the very low BS-$_{CEC7}$ recorded according to [38] scale. In addition, these saturation levels decreased with increasing depth and acidity of the horizons, from 11.07% at the surface to 4.67% in depth. According to [89] rating, the exchange complex of all the horizons were desaturated (BS-$_{CEC7}$ <20%) and these desaturation increased with depth increment and the nature of the horizons. According to [69], desaturated soils are generally highly to slightly acidic, as it was the case for soils under *F. stipulosa*, with a mean pH value of 5.44 ± 0.24. This desaturation could be attributed to increase leaching of exchangeable bases from the complex and their substitution by H$^+$ ions resulting either from biological activities or from the fixation of water molecules on Al^{3+} found in the clay slips and that became exchangeable at low pH values [91]. Indeed, for pH values <5.5, aluminum becomes exchangeable, disrupting the normal development of plants through aluminum toxicity [92]. The latter acts by blocking phosphorus that insolubilizes as aluminum phosphate and by limiting the adsorption of Ca^{2+} and Mg^{2+} through excessive occupation of the exchange sites on the complex. In addition, nutrient exports from logging, as well as poor land management practices such as bush fires and excessive drainage (very frequent in the station) could highly contribute in the decreased chemical fertility of the hydromorphic soils of the Mbo plain. It would be necessary to bring in external contributions to offset these losses if one wishes to optimize the productivity and ensure the sustainability of this ecosystem [71].

The base saturation at effective CEC (BS-$_{CECE}$) is a valuable indicator of soil fertility status in terms of real availability of nutrients [90]. The BS-$_{ECEC}$ was high in all the horizons, with values ranging from subsaturated (90.35%) to resaturated (98.11%) according to [93]. The high values of BS-$_{ECEC}$ highlighted a good availability of exchangeable cations for plants, despite their low content on soil's complex [56]. These high BS-$_{CECE}$ levels also illustrated the variable nature of existing charges on the adsorbent complex of granulometric clays (quartz, micas, and calcite) and mineralogical clays (smectites, chlorites) assumed to be very frequent in the studied profile [91]. An ideal soil should have its complex saturated with calcium, magnesium and potassium in the proportions 65/10/5 respectively [84, 90]. However, the Ca/Mg/K ratios of the horizons were 9/2/1, 5/1/1, 6/1/2 and 2/1/1 for Oapg, Apg, ABg and Bwg respectively. In order to adjust the exchange complex of the studied horizons, substantial amendments with CaO, MgO, K$_2$O can be recommended.

affected by pedogenetic processes in which water dynamic acts as a key factor in the development of these hydromorphic soil. From a physical point of view, the soil profile had a sandy clay texture at the surface, which quickly became clay with depth. Bulk density and compactness of the horizons were high, while the porosity was low, but varied with the structure and the location of the horizon within the profile. These soils were generally acidic to slightly acidic. Because of the related low pH values, exchangeable acidity and especially exchangeable Aluminium could constitute a major constraint to the proper development of intolerant plant species due to aluminum toxicity. Although the OM reserve was quite satisfactory, the low biological activity and the alternating wet and dry conditions of the soil was found to hinder mineralization, especially during flooding periods that lasted up to 5 months. Hence, organic carbon and nitrogen stocks were more or less important in some horizons depending on their susceptibility to waterlogging, their degree of aeration and microbial activity. Phosphorus levels were high to moderate in the surface, but became low with depth increment. Litter addition, anthropogenic fertilization, low pH and leaching seemed to play a major role in this unequal distribution of phosphorus between layers. Because of their high CEC$_7$, hydric soils under *F. stipulosa* were potentially fertile. This CEC$_7$ was not due to organic matter, but rather to the presence in these soils of large quantities of smectitic clay minerals with a high density of negative charges and high absorbency, as evidenced by the high values of CEC-$_{Clay}$. However, the mineral fertility was low since the soil was poor in nutrients, most of the exchange complex being occupied, thanks to the low pH by the exchangeable acidity, to the detriment of important nutrients. For these reasons, the characteristic values of the complex such as TEB, ECEC and BS-$_{CECE}$, were rather low, thus requiring adequate care in order to improve the fertility status. Such measures would involve adjusting the pH values close to neutrality by alleviating the exchangeable acidity, promoting biological activity by putting in place drainage systems and ridges. Good quality OM supply could be a more sustainable solution in case of diversification or intensification of agriculture as observed in the site. It would improve the nutrient holding capacity of the soil while restoring the balance between cations located below or beyond the optimal range, especially Ca/ Mg, K / Mg, Ca + Mg / K, Ca / TEB and K /TEB ratios. However, given some physical aspects of these soils and the presence of a fluctuating water table within the profile, an improvement of the hydraulic conductivity of the soil through the adoption of sanitation plans using ditches is advocated, provided it is well reasoned and takes into account the horizon with the lowest permeability.

CONCLUSION

Soil units characterising the natural range of *F. stipulosa* in the western highlands peripheral zone, are

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