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Research article

Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon

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ABSTRACT

Among the greatest challenges of Sub-Saharan Africa is the need for more crop production for supplying the increasing demand of its growing population. For this purpose, knowledge on soil resources and their agricultural potentials is important for defining proper and appropriate land use and management. We thus investigated on the status of soil fertility in Tombel area, in order to produce such knowledge through understanding and monitoring the impact of physicochemical properties of soil. Diverse analyses performed on various datasets demonstrated the direct impact of physicochemical properties of soil and derived soil fertility parameters on major constraints for plant growth and optimal crop production such as water retention capacity, roots development, soils aeration, nutrients availability, nutrients abundance and cations balance. Based on physicochemical soil properties, fertility parameters and Soil Quality Index (SQI), four soil fertility classes were identified in the area: (i) very good fertility soils (66 km^2) that corresponds to *Dystric Vitric Andosols* (*Melanic*) above 500m *asl*; (ii) good fertility soils (506 km^2), grouping *Dystric Vitric Andosols (Melanic)* below 500m *asl* and *Leptic Fragic Umbrisols;* (iii) fairly good fertile soils (787 km^2) including *Dystric Fragic Cambisols (Humic), Rhodic Acrisols (Cutanic Humic), Fragic Umbrisols (Arenic),* and *Mollic Ferralsols (Eutric Humic); (iv)* poorly fertile soils (375 km^2) including *Umbric Andosols (Fragic)* and *Umbric Pisoplinthic Plinthosols (Haplic Dystric)*. The principal indicators controlling soil quality in the Tombel area as derived from ANOVA and PCA analyses, are: Ca, Mg, pH water, organic matter (OM), available P, total Nitrogen and CEC. Four of the seven indicators (Ca, pH, OM, P) were also identified as important indicators for assessing the fertility status of the different soils groups in the Tombel area.

1. Introduction

One of the objectives of agriculture in the Sub-Saharan Africa is to find solutions to the demand for food for its increasing population. Since soil is fundamental for sustainable agriculture with prominent outcome on food security and living standard (Mulumba and Lal, 2008; Dumanski and Pieri, 2000), more agricultural production in this area would requires thorough knowledge of soils, their quality and their fertility status. The soil fertility status is the backbone on which all input-based high agricultural production systems can be built (Al-Zubaid et al., 2008; Parnes, 2013). It provides physical conditions and nutrients for plants growth and fructification (Marschner, 2008; Velayutham and Bhattacharyya, 2000; Foth and Ellis, 1997). Soil fertility assessment is thus, fundamental to suggest optimum conditions for plant growth (Yerima Bernard and Van Ranst, 2005).

In Cameroon, as part of Sub-Saharan Africa, soil fertility and soil quality management remains a major agricultural production problem. Knowledges on soil resources and their agricultural potentials are required as huge information's for proper and sustainable agricultural land use planning and management. However, such information on soil fertility status and soil quality are still very scarce and very localized (Martin and Sieffermann, 1966; Nyeck et al., 1999; Meyim-Dayombo, 2000; Tematio et al., 2001; Nkouathio et al., 2004; Tematio et al., 2011; Temgoua et al., 2014; Tsozué et al., 2016; Tsozué et al., 2019). There is thus, a tremendous need for assessing and understanding the soil fertility status and soil quality at national scale in order to provide land resource

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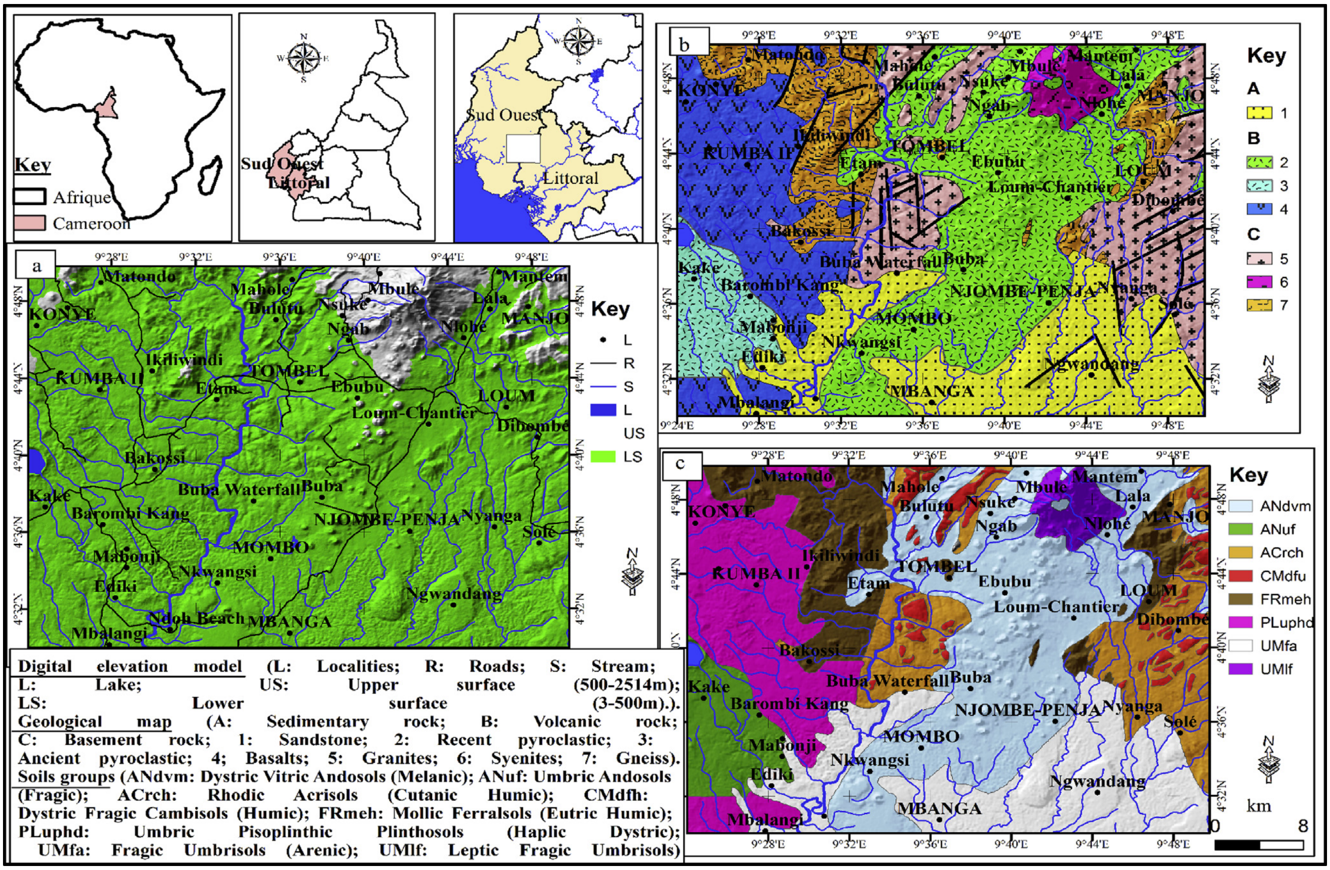

Figure 1. Regional setting of the Tombel study area, a. Digital elevation model (DEM) (L: localities; R: Roads; S: Stream; L: Lake; US: Upper surface (500–2514m); LS: Lower surface (3–500m)); b. Geological map (A: Sedimentary rock; B: Volcanic rock; C: Basement rock; 1: Sandstone; 2: Recent pyroclastic; 3: Ancien pyroclastic; 4: Basalts; 5: Granites; 6: Syenites; 7: Gneiss); c. Soil groups and distribution ((ANdvm), (ANuf), (PLuphd), (UMfa), (CMdfh), (ACrch), (UMlf); and (FRmeh)).

managers with required set of information and recommendations to increase agricultural productivity.

The Tombel area is one of the greatest areas for crop production in Cameroon (MINADER, 2013; Silatsa and Yemefack, 2017). Since decades, soils in this area have been under high agricultural pressure due to the increasing population growth and the settlement of large-scale farming companies (MINADER, 2013). In the area, soil fertility management has been identified as an important driver for increasing soils productivity (Martin and Sieffermann, 1966; Nkouathio et al., 2002; Silatsa and Yemefack, 2017). Accordingly, there is a need of assessing and monitoring physicochemical properties of soil in order to provide management strategies to ensure good and sustainable soil quality. The aim of this work is to assess of soil fertility based on physicochemical properties, soils fertility parameters and Soil Quality Index (SQI) appraisal of eight soil groups in the Tombel area. Our approach was based on monitoring the variability of soil properties, soils fertility parameters and soil quality index (SQI) under different soil groups defined according the World Reference Base for soil resources (WRB) (FAO-ISRIC, 2014); in order to produce a database that can facilitate the sustainable management of soils in this zone, particularly the sustainable management of soils developed in volcanic zones and in humid tropical forest zones.

2. The study area

The Tombel study area, located between latitudes 4°30′ and 4°50′ N and longitudes 9°24′ and 9°50′E, belongs to the South-west part of the Cameroon volcanic line (CVL) and covers a surface area of 1742 km^2 (Figure 1a). The area is under the influence of wet tropical climate with a mean annual rainfall of 2878 mm and monthly temperature varying between 22 °C and 25 °C. The study area has been divided in two landscape elevation levels (Figure 1a): The Upper and the Lower landscapes. The *Upper landscape,* with altitudes ranging between 500 and 2514 m *asl*, is a hilly landscape observed in the North-Eastern and the Northern borders of the study area. It covers a surface area of approximately 108 km^2, representing 6.2 % of the study area. The *Lower landscape,* with altitudes ranging between 3 and 500 m *asl,* covers a surface area of 1626 km^2 and represents 93.8 % of the study area. It represents the most wide-spread landscape in the study area. It exhibits a rolling landscape with a succession of smooth interfluves with flat summits delineating U-shaped valleys with parallel to locally dendritic drainage network.

Geologically, the area is formed of sedimentary, volcanic, metamorphic and plutonic rocks (Nkouathio et al., 2002) (Figure 1b). Volcanic rocks are made up of basalts and pyroclastic deposits while metamorphic and plutonic rocks are respectively gneiss and granite. Sedimentary rocks correspond mostly to sandstones. In the area, eight (08) main soil groups were described by (Nguemezi, 2019) according to the WRB (FAO-ISRIC, 2014). They are (Figure 1c): *Dystric vitric Andosols (melanic) (ANdvm)* (530km^2; 36%), *Umbric Andosols (fragic) (ANuf)* (97km^2; 6%), *Umbric pisoplinthic Plinthosols (haplic dystric) (PLuphd)* (278km^2; 16%), *Fragic Umbrisols (arenic) (UMfa)* (325km^2; 19%), *Dystric fragic Cambisols (humic) (CMdfh)* (37km^2; 2%), *Rhodic Acrisols (cutanic humic) (ACrch)* (230km^2; 14%), *Leptic fragic Umbrisols (UMlf)* (42km^2; 2%); and *Mollic Ferralsols (eutric humic) (FRmeh)* (195km^2; 11%). vegetation of the Tombel area, is generally represented by a dense tropical forest (MINADER, 2013; Silatsa and Yemefack, 2017; Nguemezi, 2019). This vegetation is strongly anthropized by plantations of perennial crops with fruit trees. There are several forest reserves in Tombel area: The Bakundu forest reserve, the Dibombé-Mabombé forest reserve, and the Loum forest reserve. According to Nguemezi (2019), in Tombel area, we have six different types of land use: water area (0.82%), forest (24.79%), built up area (6.50%), bare area (10.45%), plantation and farm (17.36%) and medium plant cover (40.08%).

3. Methods of study

3.1. Data collection and analyses

Based on a previous study by (Nguemezi, 2019), a field campaign using hand auger and hand dug bore holes was carried out in this study area to collect topsoil samples from different soil groups based on parent rocks and landscape position. Ninety-nine composite soil samples were randomly collected on the A surface horizon (topsoil) of different soil groups for physicochemical analyses. Undisturbed soil samples were also collected for bulk density. Of the one ninety-nine soil samples collected, seven are collected on *dystric vitric Andosols (melanic) > 500 m* asl, twenty-four on *dystric vitric Andosols (melanic) < 500 m asl,* ten on *umbric Andosols (fragic)*, sixteen on *umbric pisoplinthic Plinthosols (haplic dystric),* eleven on *fragic Umbrisols (arenic),* five on *dystric fragic Cambisols (humic)*, nine *on rhodic Acrisols (cutanic humic)*, four on *leptic fragic Umbrisols*, and thirteen on *mollic Ferralsols (eutric humic)*. Using an Edelman auger, under each soil group, the composite samples were collected at a depth of 0–25 cm. These soil samples were air-dried before grinding and sieving and then used for routine laboratory analysis. Physical analyses included bulk density (BD), and particle size distribution. The bulk density (BD) was obtained using the method of Koppeki cylinder (Blake, 1982). Particles size was determined by the hydrometer method (Day, 1965; Boverwijk, 1967). Chemical analyses included: organic carbon (OC), total nitrogen (N), available P, exchangeable cations (Ca, Mg, K, Na); cations exchange capacity (CEC), exchangeable Al and acidity (pH). Soil organic carbon was determined by chromic acid digestion and spectrophotometric analysis (Heanes, 1984). The total N was determined from a wet acid digest (Buondonno et al., 1995) and N analysed by colorimetric analysis using a UV-VIS spectrophotometer (Anderson and Ingram, 1993). The available P was extracted using the Bray II procedure and the resulting extract was analyzed using the molybdate blue procedure described by (Murphy and Riley, 1962). The cation exchange capacity (CEC) was obtained at pH 7 using ammonium acetate method. Exchangeable cations (Ca, Mg, K and Na) were extracted by ammonium acetate at pH7 and analyzed by flame atomic absorption spectrophotometry using the AAS (Mehlich, 1984). Soil acidity (pH) was determined in a 1:2.5 soil suspension with deionized water.

3.2. Computation of soil fertility parameters

Most soil fertility studies have been carried out in relation with major agronomic crops where fertilizer applications led to increased crop production (Dabin, 1961; Waller et al., 1975). This is evaluated on the basis of physicochemical properties and computed soil fertility parameters. The physicochemical properties commonly used are: OM, N, C/N, available P, Ca, Mg, K, Na, exchangeable Al, S (exchangeable sum of bases), CEC, textural class (TC) and bulk density (BD). These soil properties are used to calculate soil fertility parameters such as: sum of exchangeable cations (S); Forestier index (IF), soils aggregate stability index (ISS), soil sealing index (IB), and Kamprath index (m). S is obtained by summing up exchangeable cations which are: Ca. Mg. K and Na.

Soil aggregate stability index (ISS) relating soil resistance to external disruption forces was assessed using the following Pieri's formula Eq. (1) (Pieri, 1992):

$$ISS = \frac{1.724 \times OC}{(L + A)} X100 \tag{1}$$

with *OC.* the soil organic carbon; *L.* the silt fraction; and *A.* the clay fraction. An ISS>9% indicates stable structure, 7% < ISS≤9% indicates low risk of structural degradation, 5% < ISS≤7% indicates high risk of degradation, and ISS≤5% indicates structurally degraded soil.

Soil sealing index (IB) related to the risk of soils erosion and compaction was estimated using Remy formula Eq. (2) (Remy and Marin-Laflèche, 1974):

$$IB = \frac{(1.5\, x\, Lf) + (0.75\, x\, Lg)}{(A - 10\, x\, OM)} - C \tag{2}$$

with *C* equal to *0.2 x (Ph–7)*; *Lf.* the fine silt; *Lg.* the coarse silt; *A.* the clay; and *OM.* the soil organic matter content. An IB < 1.4, indicates soils without risk of thrust and without risk of erosion; 1.4 < IB ≤ 1.6, indicates soils with a low risk of erosion; 1.6 < IB ≤ 1.8, indicates soils with a medium risk of erosion; IB ≥ 1.8 indicates soils with high risk of erosion.

Forestier index (IF) was assessed using the following formula Eq. (3) (Forestier, 1960):

$$IF = \frac{S^2}{(A + Lf)} \tag{3}$$

with *S.* the sum of exchangeable cations; *A.* the clay fraction; and *Lf.* the fine silt fraction. An IF < 1.5, indicates soils with low nutrient reserves, and an IF > 1.5 indicates soils with good nutrient reserves.

Aluminium toxicity is defined by the Kamprath index Eq. (4) (Kamprath, 1970), for determining the degrees of toxicity of exchangeable aluminium. It is the ratio

$$m = \left(Al^{3+} X \frac{100}{S + Al^{3+}} \right) \tag{4}$$

Al^{3+} = exchangeable aluminium in meq:100g of soil, and S = sum of exchangeable bases in meq:100g of soil. If m < 20%, indicates soils with aluminium toxicity; 20 < m (%) < 50, indicates soils with high aluminium toxicity; and m > 50 %, indicates soils with very high aluminium toxicity.

In addition to the other soil fertility parameters, the sum of exchangeable bases (S), and the cation exchangeable capacity (CEC) were grouped into classes, allowing these results to be appreciated. When S < 2meq/100g, it indicates very low values; 2 < S (meq/100g) < 5, indicates low values; 5 < S (meq/100g), it indicates average values; 10 < S (meq/100g) < 15, it indicates high values; S > 15 meq/100g, it indicates very high values (Beernaert and Bitondo, 1992). When the CEC <5 meq/100g, indicates very low values; 5 < CEC (meq/100g) < 10, indicates low values; 10 < CEC (meq/100g) < 25, indicates average values; 25 < CEC (meq/100g) < 40, indicates high values; and CEC >40 meq/100g, indicates very high values (Beernaert and Bitondo, 1992).

3.3. Analyzing soil fertility parameter equilibriums

Some balances have been established between the physicochemical soil properties such as textural class, pH and nutrient concentrations, reported on binary and ternary diagrams according to models used by FAO-ISRIC, 2014, Forestier (1960), Dabin (1961) and Martin (1979). The textural diagram of FAO shows different textural classes of soils in relation to their agronomic interest. The triangular diagram of Dabin (1961) indicates the poles of relative richness in a given cation in the equilibrium of the cationic balance (Ca/Mg/K). Soil pH is a measure of the concentration of free H^+ protons in the soil solution. It is a very important parameter that directly influences the chemical reactions in the soil and the availability of nutrients in form that can be assimilated by plants. Soil pH, a reflection of the physicochemical conditions of the soil solution,

Table 1. Summary statistics of the original soil variables (sample population n = 99 samples).

Stats	Min	Max	Mean	Sd	VC (%)	Skewness	Range	Kurtosis
Ca (meq:100g)	0.23	31.45	4.74	4.87	103	2.45	31.22	9.44
Mg (meq:100g)	0.01	6.22	1.65	1.46	88	1.08	6.21	0.63
K (meq:100g)	0.01	1.81	0.32	0.36	114	2.06	1.79	4.35
Na (meq:100g)	0.01	0.24	0.05	0.04	90	2.48	0.23	6.77
Al (meq:100g)	0.00	2.69	0.45	0.61	13	1.71	2.69	2.66
S (meq:100g)	0.41	34.08	6.76	6.07	89	1.71	33.67	4.38
CEC (meq:100g)	4.93	53.37	16.49	8.94	54	1.35	48.44	2.27
S:CEC (%)	3.80	73.97	35.87	17.90	50	-0.04	70.17	-0.98
P (ppm)	0.31	91.12	7.72	12.27	159	4.38	90.80	23.85
OM (%)	1.26	10.80	4.43	2.21	50	1.10	9.54	0.58
N (%)	0.07	0.81	0.25	0.15	62	1.57	0.74	2.28
C/N	7.75	17.88	10.82	1.64	15	1.25	10.13	3.96
pHwater	3.57	6.96	5.07	0.74	14	0.19	3.39	-0.71
Sand (%)	9.18	85.54	49.25	20.59	42	-0.21	76.36	-1.07
Clay (%)	6.68	76.90	35.39	21.51	61	0.36	70.22	-1.12
Silt (%)	4.36	29.57	15.35	6.69	43	-0.59	43.93	2.83
BD (g:cm^3)	0.56	1.71	1.06	0.26	25	0.46	1.15	-0.61
IB (%)	-1.86	24.82	-1.01	7.67	763	-1.23	55.42	7.44
ISS (%)	1.45	48.24	11.30	9.02	80	1.60	46.79	2.67
IF	0.00	42.38	2.23	5.32	238	5.48	42.38	35.80
m (%)	0.00	83.44	15.72	22.83	145	1.47	83.44	1.03
Mg/K	0.08	173.77	11.01	20.89	190	5.52	173.69	38.44
Ca/Mg	0.77	89.76	5.24	11.10	211	5.68	88.99	36.94
Ca/K	0.48	217.44	27.70	35.07	127	2.84	216.96	10.25
(Ca + Mg)/K	0.81	342.09	38.71	51.07	132	3.30	341.27	14.18
SQI	4.44	33.45	13.55	6.66	49	1.04	29.00	0.82

Min: minimum; Max: maximum; Sd: standard deviation; CV: coefficient of variation; S (sum of exchangeable bases), SQI: Soil Quality Indices.

has a direct effect on the bioavailability of nutrients through solubilization and insolubilization phenomena specific to each element (Merelle, 1998). K and Mg, and Ca and Mg, in the absorbing complex exhibit antagonisms or synergies. The binary diagram of Dabin (1961) makes it possible to highlight these antagonisms or synergies between the Ca, Mg and K cations in the soil. These cations play plastic and physiological roles in soils (Merelle, 1998). Soil pH is closely related to the sum of bases present in the soil (Meyim-Dayombo, 2000). Indeed, pH being a measure of the H^+ concentration in the soil, the more H^+ there is, the less it can have cations such as Ca^{2+}; Mg^{2+}; K^+; and Na^+ in soil. So, the more acidic the soil, the less it contains bases. Soil pH reflects the state of saturation in bases of the absorbing complex.

3.4. Computation of soil quality index (SQI)

Calculating soil quality consists in combining the physicochemical and biological properties of the soil that are easily changeable in response to variations in soil conditions (Blake, 1982; Brejda et al., 2000). The different steps to calculate the SQI have described in the works of Ngo-Mbogba et al. (2015). With reference to previous work in in Southern Cameroon and elsewhere, ten indicators were selected for this study (Ngo-Mbogba et al., 2015). They are: OM, pH water, CEC, Ca, Mg, K, C/N ratio, available P, exchangeable Al and N. This dataset of indicators focused more on soil chemical parameters because some authors (Yemefack et al., 2006; Ngo-Mbogba, 2009) reported their utmost important influence and manifestation on crops growth characteristics.

Each indicator was normalized by Ngo-Mbogba et al. (2015), and the SQI parameter was calculated by the method described by Eq. (5) (Andrews et al., 2002).

$$SQI = \sum_{i=1}^{n} WiXi \qquad (5)$$

W is the normalized indicator; X is the indicator score; SQI is the soil quality index; i is a soil property and n, the number of soil properties.

3.5. Statistical analysis

Descriptive statistics were calculated on 25 variables because some soil properties are less dynamic than other. Nine variables cited in section 3.4, showing significant variation were then selected for further analyses. One-way ANOVA was performed to assess the influence of different soil groups on soil chemical properties (OM, Bray P, Ca, Mg, K, Al). The separation of means between the different soil groups was made using the Tukey's test. The most appropriate soil quality indicators have been selected by applying the principal component analysis. Excel 2013 and R (R, 2012) were used to perform these analyses.

4. Results and discussions

4.1. Summary statistics

The statistics of the 25 soil variables obtained on the different soil groups are summarized in Table 1. Most of them show a positive skewness varying between 0.19 and 5.68; meaning that the mean is usually greater than the median, which is also greater than the mode; except for sands, silts, sealing index (IB), and base saturation (S: CEC) showing negative skewness varying between -0.04 and -1.23. Those variables with skewness less than -1 or greater than 1, are skewed meaning that the right tail of the distribution is longer than the left for positive skewness and the reverse for negative skewness. The kurtosis is also highly variable, with some values greater than 1 or less than -1. This departure of the skewness and the kurtosis for zero means that most of these variables have a slight abnormal distribution. Fortunately, ANOVA is not a very sensitive to moderate deviations from normal, because simulations studies, shown

Table 2. Soils chemical characteristics of the surface layer (0–25 cm) sampled under different land cover types (n = 99 samples).

Soil groups	MO (%)	N (%)	C/N	CEC (meq:100g)	Sand (%)	Clay (%)	Silt (%)	ISS (%)	IF	(Ca + Mg)/K	BD (g/cm^3)
PLuphd	3.6 ± 1.6a	0.2 ± 0.1	10.5 ± 1.0ab	13.7 ± 6.2ab	34.1 ± 13.3qb	51.0 ± 15.88cd	14.8 ± 6.9ab	5.9 ± 3.4a	0.8 ± 1.1b	44.7 ± 26.5b	1.2 ± 0.3b
FRmeh	3.5 ± 1.6a	0.2 ± 0.1a	10.9 ± 1.4ab	8.7 ± 8.4a	46.9 ± 14.9acd	41.3 ± 17bd	11.8 ± 9.7a	6.4 ± 2.9a	1.9 ± 5.6ab	22.1 ± 20.0ab	1.1 ± 0.2ab
UMfa	3.6 ± 1.5a	0.2 ± 01a	12.4 ± 2.1b	15.2 ± 8.4ab	62.7 ± 18.1cd	24.2 ± 14ab	13.0 ± 5.2	12.1 ± 8.4a	3.1 ± 6.5ab	36.5 ± 35.4ab	1.1 ± 0.2ab
UMlf	6.2 ± 2.8ab	0.3 ± 0.1a	11.2 ± 0.9ab	19.9 ± 6.1abc	66.1 ± 9.0cd	16.2 ± 8.1	17.6 ± 2.3	17.8 ± 3.9ab	1.5 ± 0.8ab	10.5 ± 0.4ab	0.7 ± 0.1a
CMdfh	4.3 ± 2.2ab	0.2 ± 0.1ab	10.5 ± 1.1ab	15.1 ± 4.1ab	67.8 ± 1.5cd	17.7 ± 5.8ab	14.5 ± 7.6ab	14.0 ± 6.5ab	1.4 ± 3.1ab	18.9 ± 10.2ab	1.2 ± 0.3ab
ACrch	4.5 ± 1.9a	0.2 ± 0.1a	11.3 ± 1.1ab	13.8 ± 4.9ab	66.4 ± 9.3d	20.7 ± 8.6ab	12.9 ± 4.6a	13.1 ± 6.0ab	0.9 ± 1.4ab	13.2 ± 8.7a	1.2 ± 0.3ab
ANdvm>500m	7.8 ± 1.9b	0.5 ± 0.1b	9.5 ± 1.0a	30.6 ± 11.9c	65.8 ± 7.7cd	11.0 ± 7.1a	23.1 ± 4.1b	24.3 ± 8.7b	8.4 ± 13.3a	53.2 ± 80.6ab	0.9 ± 0.3ab
ANdvm<500m	5.1 ± 2.3a	0.3 ± 0.2a	9.51 ± 1.9a	19.1 ± 7.8b	45.6 ± 22.3bc	37.3 ± 23.5bc	17.1 ± 5.6ab	13.0 ± 11.5a	2.3 ± 2.4ab	36.9 ± 43.9ab	0.9 ± 0.2a
ANuf	3.2 ± 1.3a	0.2 ± 0.1a	10.3 ± 1.6ab	11.6 ± 5.0ab	26.5 ± 9.3a	57.7 ± 11.7d	15.8 ± 5.5ab	4.2 ± 2.2a	0.4 ± 0.5ab	88.7 ± 106.1a	1.1 ± 0.2ab

Values followed by the same letters are not statistically different ($p < 0.05$) according to least significative difference (Tukey's test). PLuphd = *umbric pisoplinthic Plinthosols (haplic dystric)*, FRmeh = *mollic Ferralsols (eutric humic)*, UMfa = *fragic Umbrisols* (*arenic*), UMlf = *leptic fragic Umbrisols*, CMdfh = dystric fragic Cambisols (humic), ACrch = rhodic Acrisols (cutanic humic), ANdvm>500m = *dystric vitric Andosols (melanic)* above 500m high, ANdvm<500m = *dystric vitric Andosols (melanic)* below 500m high, ANuf = *umbric Andosols (fragic)*.

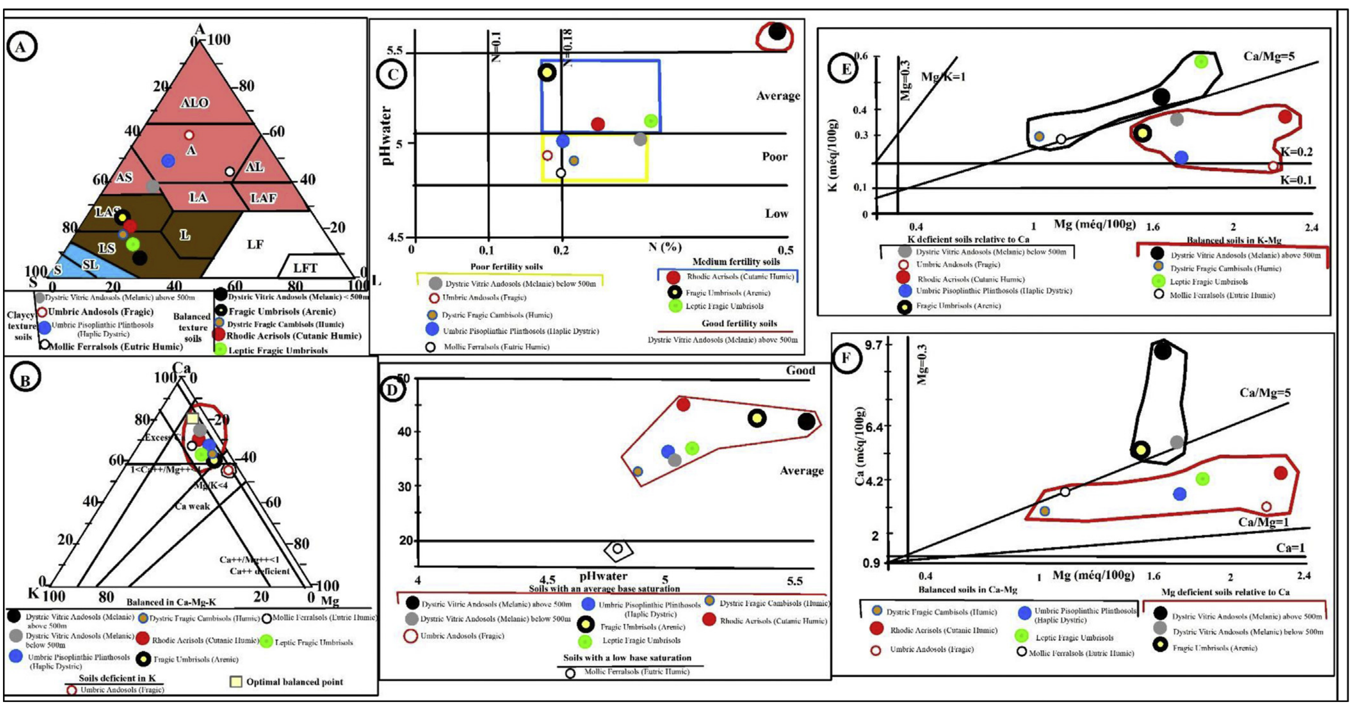

Figure 2. Graphs of the soils fertility parameters equilibriums in the Tombel plain. a. Soils textural class; b. Ca–Mg–K equilibrium; c. N-pH equilibrium; d. S:CEC – pH equilibrium; e. K–Mg equilibrium; f. Ca–Mg equilibrium.

that the rate of false positives is not very affected by this violation of the normality assumption (Lix et al., 1996).

Except for Al, pH and C/N with of coefficient of variation (CV%) around 15%, all other variables have high to very high CV, meaning that there is a high variability of soil parameters and SQ (soil quality) within soil groups in Tombel area. Computed indices such as IB (from Particle size, OM, pH) and IF (Particle size and Exchangeable bases), derived from the combination of several parameters showed the highest rate CV, following by exchangeable bases and their derived ratios. These CV seem to be controlled by a multiplying effect from various input parameters.

4.2. Variability of soils properties and soils fertility parameters across soils groups

From summary statistics of the 25 variables from 8 soil groups, 12 variables identified as the most variable (OM, N, C/N, CEC, Sand, Clay, Silt, ISS, m, IF, (Ca + Mg)/K) and BD), were used for ANOVA and mean separations (Tukey's HSD). The results presented in Table 2 show a great variability of significantly differences from one soil to another.

The organic matter content showed a significant difference between *dystric vitric Andosols (melanic)* above 500m high and other soil groups, namely *umbric Andosols (fragic), mollic Ferralsols (eutric humic)*, *umbric pisoplinthic Plinthosols (haplic dystric), fragic Umbrisols (arenic)* and *rhodic Acrisols (cutanic humic)*. This significant difference between *dystric vitric Andosols (melanic)* above 500m high and other soil groups can be explained by the double protection between the latter and free aluminum, as reported in many *Andosols* (Tématio, 2005). On the other hand, the slight difference between *dystric vitric Andosols (melanic)* at different altitude may be due to altitude effect (Tsozué et al., 2019) or to human activities more pronounced in lower altitude. CEC also shows a significant difference between several soil groups. Soils with higher CEC have an important nutrients reserve (high IF). This important nutrients reserve and high CEC are associated with high levels of OM in these soils (Omoko, 1996; Yerima Bernard and Van Ranst, 2005).

The structural stability index (ISS), sand and clay showed a significant difference between several soil groups. The good structural stability of *dystric vitric Andosols (melanic)* above 500m high is assigned to high levels of OM and the clay fraction which favour the aggregation of soil particles

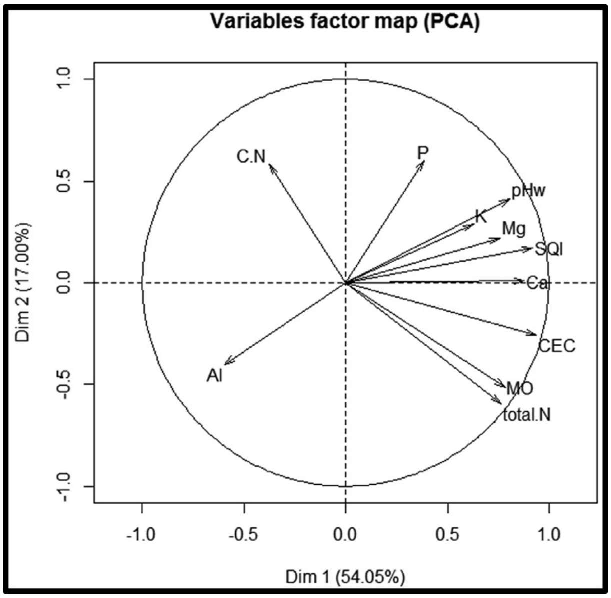

Figure 3. Variable factor map PCA: principal component analysis; SQI: soil quality index; OM: organic matter; C:N ratio; CEC: Cation exchange capacity; Mg: magnesium; pHw: pH water; Al: Aluminium, P: phosphorous; Ca: calcium; K: potassium.

(Lal, 1994). The combination of clays and humic compounds in the clay-humic complex results in the formation of aggregates, basic elements of soil structure in the upper horizons. These colloidal lumps contribute to the formation of an airy structure by allowing moreover a better retention of water in soils.

4.3. Variability of fertility parameters equilibriums across soils types

The FAO Textural Diagram based on the Tombel soils data (Figure 2a) defines two soil texture groups: clayey textured soils and balanced textured soils. Soils with clayey texture are *dystric vitric Andosols (melanic)* below 500 m high, *umbric Andosols (fragic), umbric pisoplinthic Plinthosols (haplic dystric)* and *mollic Ferralsols (eutric humic)*. Balanced textured soils include *dystric vitric Andosols (melanic)* above 500 m high, *fragic Umbrisols (arenic), dystric fragic Cambisols (humic)* and *rhodic Acrisols (cutanic humic)*.

The triangular diagram of Dabin (1961), adapted to the Tombel soils (Figure 2b), indicates that all the soils are close to the optimal equilibrium, except the *umbric Andosols (fragic),* showing K deficient. In reference to acidity, the Dabin (1961) diagram has defined three classes of soil fertility (Figure 2c): poor fertility soils, average fertility soils and good fertility soils. Soils showing poor fertility have a pH between 4.75 and 5.1. These include *umbric pisoplinthic Plinthosols (haplic dystric), dystric vitric Andosols (melanic)* below 500 m high, *umbric Andosols (fragic), dystric fragic Cambisols (humic)* and *mollic Ferralsols (eutric humic)*. They show no N deficiency, except for *umbric Andosols (fragic)*. Soils showing average fertility have a pH between 5.1 and 5.5, with no N deficiency, except for *fragic Umbrisols (arenic)*. They include *fragic Umbrisols (arenic), rhodic Acrisols (cutanic humic)* and *leptic fragic Umbrisols*. Soil showing good fertility is *dystric vitric Andosols (melanic) above 500m high* with have a pH greater than 5.5.

According to Martin's binary fertility plot (1979), all the soil groups are above the Mg and Ca deficiency thresholds (Mg = 0.3 meq:100g) and Ca (Ca = 1 meq:100g) (Figure 2f). This diagram groups the soils of Tombel plain into two broad classes: soils balanced in Ca and Mg ($1 <$ Ca:Mg < 5) and soils deficient in Mg relative to Ca (Ca:Mg > 5). The class of balanced soils in Ca and Mg includes *umbric Andosols (fragic), umbric pisoplinthic Plinthosols (haplic dystric)*, *leptic fragic Umbrisols, dystric fragic Cambisols (humic), rhodic Acrisols (cutanic humic)* and *mollic Ferralsols (eutric humic)*. Deficient soils in Mg are *dystric vitric Andosols (melanic)* and *fragic Umbrisols (arenic)*.

The balance between the saturation rate (S: CEC) and acidity (pH) makes it possible to highlight the impact of pH on the evolution of exchangeable bases in the soil. The related diagram (Figure 2d) groups the *Tombel plain* soils into two broad classes: soils with a low base saturation (S: CEC $\leq$20%) and soils with a medium base saturation ($20 <$ S: CEC (%) <50). The class of soils with low base saturation rate includes only *mollic Ferralsols (eutric humic)*. The soil class with average saturation level includes all the other soils groups.

4.4. Soil quality index of different soils groups

4.4.1. On the SQI parameter

SQI_{10} was calculated from ten (10) indicators (OM, pH water, available P, Ca, Mg, K, Al, C/N ratio, CEC and N). SQI_6 was calculated using six indicators (OM, CEC, pHw, Mg, and Ca), respectively depending on the

Table 3. Criteria for Evaluating Soil Fertility Classes (Quemada and Cabrera, 1995 modified).

Characteristics	Class 1 (no limitation)	Class 2 (average limitation)	Class 3 (severe limitation)	Class 4 (very severe limitation)
MO (%)	>2	1–2	0.5–1	<0.5
N (%)	>0.08	0.045–0.08	0.03–0.045	<0.03
P (ppm)	>20	10–20	5–10	<5
K (meq:100g)	>0.4	0.2–0.4	0.1–0.2	<0.1
S (meq:100g)	>10	5–10	2–5	<2
S:CEC (%)	>60	40–60	15–40	<15
CEC (meq:100g)	>25	10–25	5–10	<5
pH	>5.5	5.1–5.5	4.75–5.1	<4.75
IB (%)	≤1.4	1.6–1.4	1.8–1.6	≥1.8
IF	>1.5	-	-	<1.5
ISS (%)	>9	7–9	5–7	<5
m (%)	>60	40–60	20–40	<20
SQI	>19	13–19	10–13	<10

PLuphd = umbric pisoplinthic Plinthosols (haplic dystric), FRmeh = mollic Ferralsols (eutric humic), UMfa = fragic Umbrisols (arenic), UMlf = leptic fragic Umbrisols, CMdfh = dystric fragic Cambisols (humic), ACrch = rhodic Acrisols (cutanic humic), ANdvm>500m = dystric vitric Andosols (melanic) above 500m high, ANdvm<500m = dystric vitric Andosols (melanic) below 500m high, ANuf = umbric Andosols (fragic).

Table 4. Synthesis on the evaluation of soil group fertility in the Tombel plain.

Soils groups	OM (%)	SQI	N (%)	P (ppm)	K (méq:100g)	S (méq:100g)	S:CEC (%)	CEC (méq:100g)	pH	IB	IF	ISS	m (%)	Fertility level	Limiting factors
ANdvm >500 m	I	I	I	III	I	I	I	I	I	I	I	I	I	Very good	P
ANdvm< 500 m	I	II	I	III	II	II	II	II	II	I	I	I	II	Good	P, K
ANuf	I	II	I	III	II	II	II	II	III	IV		IV		Poor	P, K, IB, ISS
PLuphd	I	II	I	III	II	II	II	II	III	III	III	III	I	Poor	IB, ISS, P, K
UMfa	I	III	I	IV	II	II	II	II	II	I	I	I	I	Average	K, P, SQI
CMdfh	I	II	I	III	I	II	II	II	III	I	I	I	I	Average	K, P, S, pH
ACrch	I	II	I	III	II	III	II	II	II	I	II	I	I	Average	CEC, S, K, P
UMlf	I	I	I	III	I	II	II	II	II	I	I	I	I	Good	P, K
FRmeh	I	II	I	III	II	II	II	III	III	II	I	II	II	Average	P, pH, CEC, S/CEC

PLuphd = umbric pisoplinthic Plinthosols (haplic dystric), FRmeh = mollic Ferralsols (eutric humic), UMfa = fragic Umbrisols (arenic), UMlf = leptic fragic Umbrisols, CMdfh = dystric fragic Cambisols (humic), ACrch = rhodic Acrisols (cutanic humic), ANdvm>500m = dystric vitric Andosols (melanic) above 500m high, ANdvm<500m = dystric vitric Andosols (melanic) below 500m high, ANuf = umbric Andosols (fragic).

solid relationships that exist between them and their correlated group as shown the biplot of Figure 3. The effect of the number of indicators on the SQI was assessed using the SQI (SQI10, SQI6) to assess the absolute variation between the two. This difference will allow us to know if with a combination of a few parameters, we could assess the soil quality.

The *leptic fragic Umbrisols* (UMlf) ($SQI_{10} = 33 \pm 6$ $SQI_6 = 12 \pm 6$) and *dystric vitric Andosols (melanic)* above 500m high (ANdvm>500m) ($SQI_{10} = 19 \pm 8$; $SQI_6 = 12 \pm 9$) showed a very high SQI. These are soils located at the top and on the slopes of Mount Koupé, at an altitude above 500m; they are under a very dense natural cover. According to (Andrews et al., 2002; Nurullah, 2019; Demirağ Turan et al., 2019), better soil fertility is indicated by a high soil quality index. Undisturbed naturel land has good soil quality (Doran and Parkin, 1994; Dengiz, 2019). Those on ACrh ($SQI_{10} = 19 \pm 8$; SQI_6: 7 ± 7), CMdfh (SQI_{10}: 19 ± 4; SQI_6:11 ± 7); and PLuphd (SQI_{10}: 16 ± 6 SQI_6: 9 ± 7) showed high SQI. ANuf (SQI_{10}: 15 ± 8; SQI_6: 10 ± 7); FRmeh (SQI_{10}: 14 ± 7; SQI_6: 8 ± 7) and ANdvm<500m (SQI_{10}: 14 ± 5; SQI_6: 9 ± 5) and UMfa (SQI_{10}: 13 ± 8; SQI_6:8 ± 7) showed an average soil quality.

4.4.2. Correlating SQI with soil parameters

Two main axes define the classification of soil chemical properties in spaces. The most appropriate indicators that determine soil quality have been selected by subjecting the values of soil chemical properties to principal component analysis (PCA). The first two principal components (PCs) explained around 71.6% of total variation: 54.03% explained by PC1 and 16.9% by PC2. PC1 had loading by pHw, Ca, Mg, OM, available P and CEC.

There is a strong correlation between Ca, Mg, pHw, OM, available P, total nitrogen and CEC (Figure 3). Ca, Mg, pHw, OM, available P, total nitrogen and CEC are the main indicators controlling soil quality in Tombel area.

4.5. Soils fertility status

The statistical analysis of the physicochemical properties, the fertility parameters and the soils quality index as well as the balances between these parameters made it possible to evaluate the current state of fertility of the identified soil groups in the *Tombel plain*; by grouping them into fertility classes according to (Quemada and Cabrera, 1995) modified, which according to the limitations in question and their degree of intensity, defined the following classes (Table 3):

- ➢ Class I: soil characteristics are not present or present only weak limitations;
- ➢ Class II: soil characteristics do not have more than 3 moderate limitations possibly associated with low limitations;
- ➢ Class III: soil characteristics have more than 3 moderate limitations possibly associated with a single severe limitation;
- ➢ Class IV: soil characteristics have more than one severe limitation.

Table 4 shows four groups of soils in Tombel area according to their fertility level.

This is:

- ❖ Class I grouping soils with a very good fertility level. These correspond to *dystric vitric Andosols (melanic)* (ANdvm) above 500 m high; with low limitations in available P.
- ❖ Class II groups soils with good fertility level. These are *dystric vitric Andosols (melanic)* (ANdvm) below 500 m high and *leptic fragic Umbrisols (UMlf)*. The *ANdvm* below 500 m high has low limitations in available P, K and S. The *UMlf* has moderate limitations in available P and soil acidity (pHw).
- ❖ Class III includes soils with average fertility level. They are *dystric fragic Cambisols (humic) (CMdfh), rhodic Acrisols (cutanic humic) (ACrch), fragic Umbrisols (arenic)* and *mollic Ferralsols (eutric humic) (FRmeh)*. The *CMdfh* have moderate limitations in available P and K, and in some extend in S; they also have a severe limitation in pHw. The *ACrch* have moderate limitations in available P, K and CEC. They present a severe limitation in S content. The *UMfa* have low limitations in K and S, and severe limitations in available P and Soil Quality Index (IQS). The *FRmeh* have moderate limitations in available P and bases saturation; and severe limitations in pHw and CEC. Bringing a calcium amendment makes it possible to promote the availability P and Mg, for the plant; to promote the installation of roots. Maintenance liming which consists of making a contribution every 3–4 years to maintain a sufficient pHw. It will be necessary to estimate the quantities according to the exports realized on the parcel (ex: mowing) and the acidifying action of the mineral fertilizers if they are brought regularly.
- ❖ Class IV includes poor fertility soils. These are *umbric Andosols (fragic) (ANuf)* and *umbric pisoplinthic Plinthosols (haplic dystric) (PLuphd)*. Both soils have low limitations in available P and K; and severe limitations in Sealing Index (IB) and soil aggregate stability index (ISS). This class of soils with poor fertility require several years of tillage for the restoration of its properties. To restore these properties, in addition to recommendations for the improvement of soils with medium fertility, several solutions are proposed. Farmers must practice the fallow system after cultivation to maintain soil fertility; to alternate the types of cultures; and promulgate new soil nutrient supply mechanisms from inputs (composts, chemical fertilizers, mineral fertilizers ...). Improve the physical fertility of soils, by: adding soil cover by plant residues, and vegetation cover, which leads to a decrease in the volume and runoff but also maintains the porosity on the surface; stimulate soil biological activity, consists of multiplying earthworms, improving soil life and improving of deep drainage; and the increase of the level of humus on the surface leads to the increase

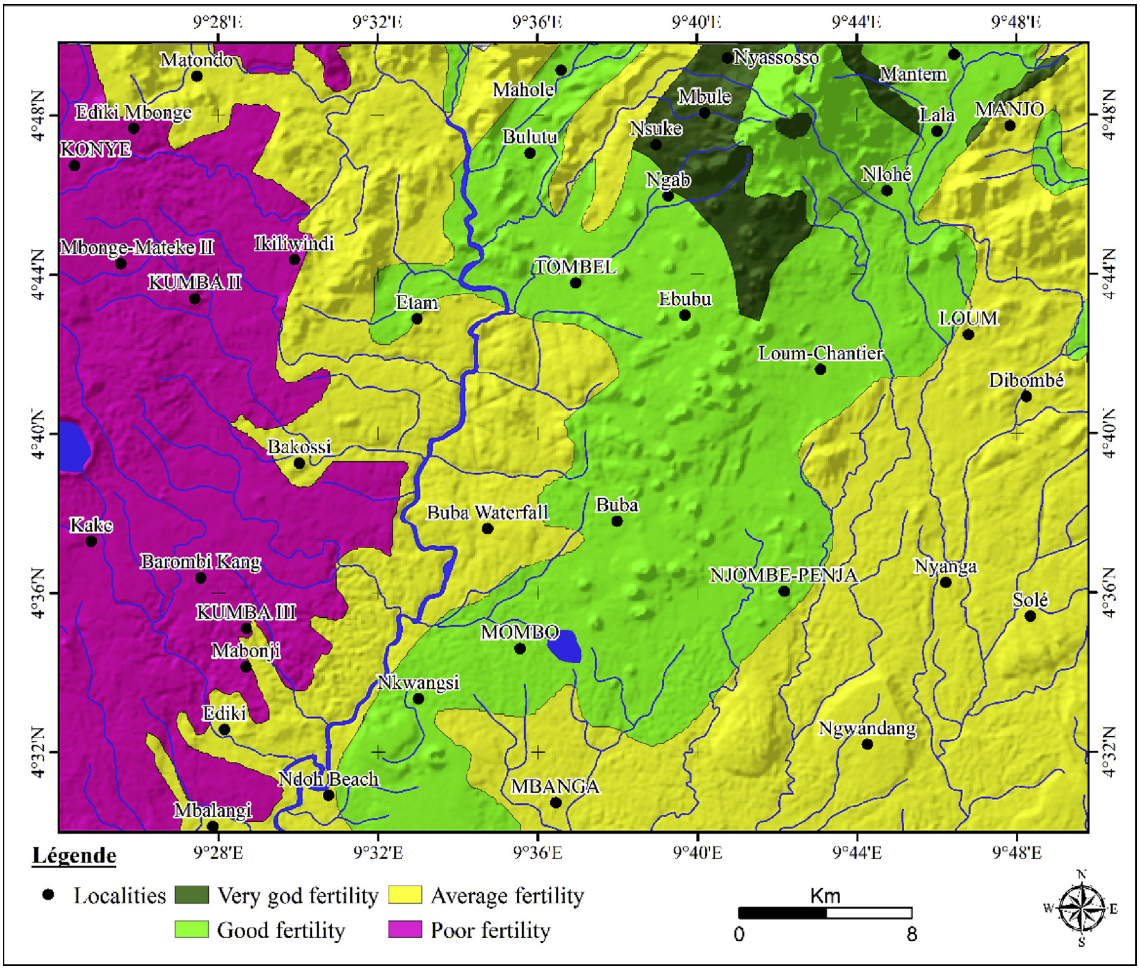

Figure 4. Fertility map of the Tombel plain study area.

of the structural stability and the decrease of the erosive risk. Rectification liming, which consists of bringing a significant quantity over several consecutive years to correct a low pHw. The inputs are made in small quantities at a time to raise the pH slowly so the mineral elements may become blocked.

The very good fertility soils represent 66km^2 (3.79%). The good fertility soils cover an area of 506km^2 (29.04%). An average fertility soils cover an area of 787km^2 (46.49%). And the poor fertility soils represent 375km^2; (21.46%) (Figure 4).

Analysis of the fertility status of each soil group shows that soils with good and very good fertility status are characterized by high to very high Soil Quality Index (SQI). This can be explained by the significant nutrient reserves (IF $>$ 1.5) and the high levels of organic matter (OM$>$ 4.2%). Soils with average fertility status are characterized by a mean Soil Quality Index (SQI); this translates their low wealth into nutrients. On the other hand, soils with poor fertility status are characterized by the low and average SQI. The poor fertility status of these soils is related to physical parameters that have severe limits (IB and ISS), because the soil quality index rather express the chemical richness of soils in nutrients (chemical properties of soils).

5. Conclusion

The objective this study was to assess the current fertility status of the different soil groups in the Tombel area, on the basis of physicochemical properties, fertility parameters and the soil quality index; in order to produce a database that can facilitate the sustainable management of soils in this zone, particularly the sustainable management of soils developed in volcanic zones and in humid tropical forest zones. All the above help at concludes that in the Tombel plain:

(i) Soil quality and soils fertility changes from one soil group to another.
(ii) Based on the physicochemical properties, fertility parameters and the Soil Quality Index (SQI), four (4) soil fertility classes were identified: class of very good fertility soils (ANdvm >500 m); class of good fertility soils (ANdvm <500 m, UMlf); class of average fertile soils (CMdfh, ACrch, UMfa, FRmeh); and class of poor fertility soils (ANuf, PLuphd).
(iii) According to PCA, the main indicators controlling soil quality in Tombel are: Ca, Mg, pHw, OM, available P, total N and CEC.
(iv) The major problem Tombel soil groups is the low levels of available phosphorus in soils, which is a typical problem of tropical soils.

Some suggestions of inputs best suited to these soils, and if possible, corrected all the failures of the fertility of each soil groups could be listed here below. The restoration of soil properties limiting fertility in the Tombel area depends on the level of fertility, limiting factors and their degree of limitation.

In the Tombel plain, 33% of soils with very good and good fertility are favorable for efficient farming practice; despite low limits in available phosphorus and mainly in calcium while 46.49% of soils with medium fertility require fertilizer input and a short-term correction to support good agricultural development. The recommended actions are:

- ❖ Bringing a calcium amendment makes it possible to reduce the toxicity to aluminum; to promote the availability P, Mg; to promote the installation of roots and increase the calcium content of the grass and to improve soil structural condition for soils low in organic matter with low CEC.
- ❖ Maintenance liming which consists of making a contribution every 3–4 years to maintain a sufficient pHw. It will be necessary to estimate the quantities according to the exports realized on the parcel (ex: mowing) and the acidifying action of the mineral fertilizers if they are brought regularly.

On the other hand, 21.5% of soils with poor fertility require several years of tillage for the restoration of its properties. To restore these properties, in addition to recommendations for the improvement of soils with medium fertility, we can:

- ❖ Farmers must practice the fallow system after cultivation to maintain soil fertility; to alternate the types of cultures; and promulgate new soil nutrient supply mechanisms from inputs (composts, chemical fertilizers, mineral fertilizers, etc.).
- ❖ Improve the physical fertility of soils, by: adding soil cover by plant residues, and vegetation cover, which leads to a decrease in the volume and runoff but also maintains the porosity on the surface; stimulate soil biological activity, consists of multiplying earthworms, improving soil life and improving of deep drainage; and the increase of the level of humus on the surface leads to the increase of the structural stability and the decrease of the erosive risk. Rectification liming, which consists of bringing a significant quantity over several consecutive years to correct a low pHw. The inputs are made in small quantities at a time to raise the pH slowly so the mineral elements may become blocked.

Declarations

Author contribution statement

C. Nguemezi, P. Tematio, M. Yemefack, D. Tsozue, T.B.F. Silatsa; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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