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Predicting soil Cation Exchange Capacity (CEC) from pH, percentage of Clay and Organic Carbon : A Case Study on Selected Burundi Surface Soils

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ABSTRACT

A statistical linear regression study was performed on surface soil samples collected in four Burundi agro-écological zones (AEZ) of Imbo, Mumirwa, Kirimiro and Moso. The study aimed at evaluating the causal effects of soil pH, % clay and % Organic C (OC) on soil cation exchange capacity (CEC), using simple, two-way and 3-way linear regression models. Soil pH as an explanatory variable of CEC gave poor results, while % OC emerged as the best one-way explanatory variable of CEC (R^2=0,40). With 2-way regression analyses, the best fits were obtained in the Kirimiro AEZ with soil pH and % clay (R^2=0,63), Imbo AEZ with soil pH and % OC (R^2=0.66) and Imbo and Kirimiro AEZ with % clay and % OC (R^2=0,63). The 3-way (pH, % clay and % OC) regression analysis gave statistically significant higher R^2 values ranging from 0.60 (Mumirwa) to 0.76 (Imbo). Linear regression analysis performed on pooled data (256 samples) proved that the 3-way dependent/explanatory variables model is the best fit (R^2=0,64). In conclusion, our results outlined that % OC emerges as the key determinant of CEC in highly weathered, kaolinitic Burundi soils.

Keywords: Burundi, CEC, pH value, Clay percentage, Percentage of Organic C, Linear regression, Surface soils.

1. INTRODUCTION

Soil cation exchange capacity (CEC), pH and soil organic C (organic matter) are three of the most influential soil parameters with regard to soil physical, biological and chemical properties as well as soil productivity [1-2]. Soil CEC is the total exchangeable cations that a soil can hold at a specified pH [2, 9, 28, 30]. CEC depends on soil pH, type, size and amount of clay, source and level of organic matter decomposition [2-11]. Cation exchange capacity (CEC) originates from negative charges from dissociation of organic matter functionnal groups and permanent (2:1), as well as variables, pH-dependent charges (2 :1, 1 :1) on clay minerals and soil organic matter [9]. Most predictive models of CEC use clay mineral compositition and organic C and their combination [8-9, 10, 12-13]. Few studies use soil pH as an independent explanatory variable of soil CEC [12, 14-16].

The majority of soil scientists advance that it is economic to exploit a method using soil physical and chemical properties to estimate CEC, otherwise determined by laborious and time consuming laboratory methods [15, 17]. For that purpose, linear models, simple or multiple, are oftern used [3, 12, 17-20].

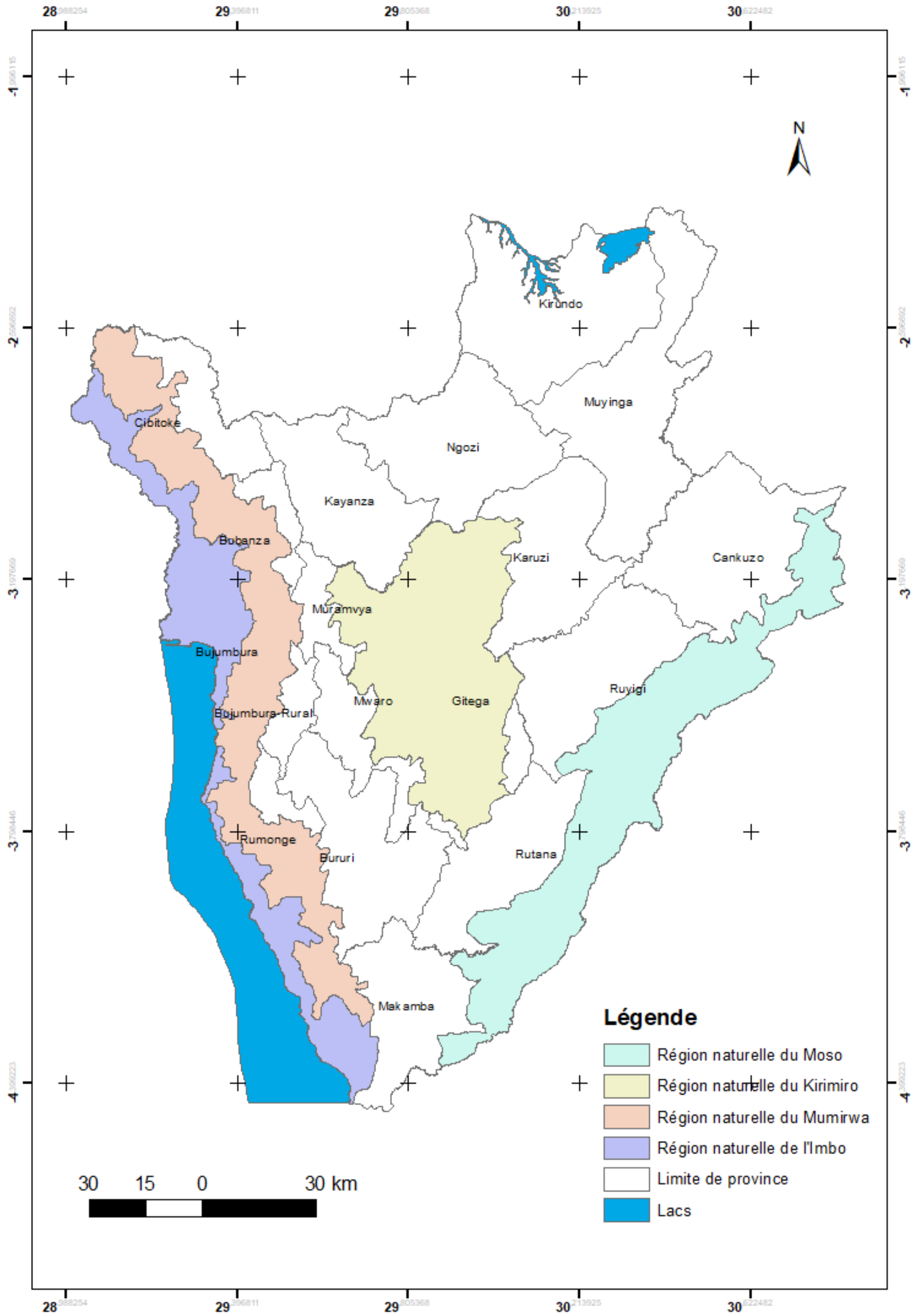

Figure 1. Geographical locations of 4 natural agro-ecological regions used in the study.

We tested both simple and multiple linear models to evaluate the relationships between CEC as an independent variable and soil pH, % clay and % Organic C as dependent variables on selected topsoils (Ap horizon) from 4 major Burundi agro-ecological regions depicted in Figure 1. They represent about 40 % of the total Burundi land as follows : Imbo (175 504 ha or 6,8 %), Mumirwa (272 317 ha or 10,5 %), Kirimiro (275 785 ha or 10,7 %) and Moso (286 547 ha or 11,1 %).

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2. MATERIALS AND METHODS

2.1 Soil Analysis

Soil data used in the study were drawn from studies conducted in selected Burundi natural (agro-ecological) regions [20]. According to these soil investigators Imbo, soils are mostly of alluvial origin with a high representation of vertisols, fluvisols and regosols. Mumirwa is dominantly characterized by ferallitic soils of the orthic and acric ferralsols. Central Plateau soils of Kirimiro are a combination of cambisols and ferraslsols, while Moso soils are essentially of the Acrisols and Luvisols groups. Used soil samples numbers (n) were as follows : Imbo (34), Kirimiro (73), Moso (83), Mumirwa (66) for a total of 256 soil samples.

Soil samples were air-dried, gently crushed and sieved with a 2-mm mesh prior to analysis : CEC, pH, % C and % clay. Organic C was determined using the Walkely-Black wet oxidation method [21]. Cation exchange capacity (CEC) was determined by the 1 M ammonium acetate saturation method (pH=7.0) [22]. Soil pH was measured in a 1:5 soil/water suspension [23]. Soil texture and % clay content were assessed by the hydrometer method [24].

2.2 Linear Regression Models

Modeling refers to mathematical expressions that link a dependent variable often denoted Y and predictor, to explanatory called independent variables and denoted X [25]. Some of the assumptions required for the pertinence of linear regressions are that : (i) the linear relationship between X and the mean of Y is linear ; (ii) the variance of residuals is the same for any value of X ; (iii) observations are independent of each other. The explanatory or independent variables are assumed constants.

Linear models involve constants named parameters which control the models. Linear models imply that the parameters are simple coefficients on the independent variable. The simple linear model involves only one independent variable and one dependent variable and states that changes in the dependent variable are affected with a constant rate as the value of the independent variable increases or decreases [25].

Linear regression can be multiple when several explanatory variables are used to predict the outcome of a response (dependent) variable. Parameter estimates depict the change in the response associated with a one-unit change of the predictor, all other predictors being held constants. They are determined by the least-squares estimation [25]. An important measure of the contribution of the independent variable in the linear or any other model is the coefficient of determination, denoted R^2. It is the proportion of the (corrected) sum of squares of Y attributable to the information obtained from the independent variable(s) [26]. The coefficicient of determination (R^2) ranges from 0 to 1. For the particular case of simple linear regression, one dependent versus one independent variable, R^2 is the square of the correlation coefficient (r). The coefficient of determination measures the adequacy of the regression model. It measures the proportion of variation in the dependent variable that is predicted by the statistical model, i.e how the regession model fits the observed data.

Linear regression model use continous variables to predict the value of an outpout (response) variable. Simple linear regression is a regression model that estimates the mathematical relationship between one independent variable and one dependent variable using a straight line. Both dependent and independent variables should be quantitative [25]. Linear model can be constructed with more than one independent variable to explain the behavior of the dependent variable Y. For more than one dependent variables, the usual least squares assumptions apply and the independent variables are also assumed to be measured without error [26].

Simple linear models are described by the following equations :

$$\mathbf{Y = ß_o + ß_1 X + \varepsilon}$$

where : Y = Independent (explained) variable (CEC); X = Dependent (explanatory) variable (soil pH, % clay, % OC) ; $ß_o$ = Y-intercept parameter ; $ß_1$ = Slope parameter of the line ; ε = Random error which encompasses for omitted factors. The slope parameter ($ß_1$) represents the amount by which change in X must be multiplied to give the corresponding average change in Y. $ß_o$ and $ß_1$ parameters are determined by the method of least squares, which finds the parameter values that

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minimize the sum of squared distances from each point of the line of fit [26]. Least squares regression is the method of fitting of a model to minimize the sum of squared residuals, a term that denotes the difference between the actual response value and the value predicted by the line of fit.

In the case of two explanatory/independent variables, the linear model is a follows :

$$\mathbf{Y = ß_o + ß_1 X_1 + ß_2 X_2 + \varepsilon}$$

where : Y=Independent (explained) variable (CEC) ; X_1=First dependent (explanatory) variable ; X_2 = Second dependent (explanatory) variable ; $ß_o$=Y-intercept parameter ; $ß_1$ = Slope parameter of the line for X_1 ; $ß_2$ = Slope parameter of the line for X_2 ; ε = Random error. $ß_1$ and $ß_2$ are partial coefficients reflecting the proportionnal change in the dependent variable Y per unit change in X_1 and X_2 independent variables.

In the case of three explanatory/independent variables, the linear model becomes :

$$\mathbf{Y = ß_o + ß_1 X_1 + ß_2 X_2 + ß_3 X_3 + \varepsilon}$$

where : Y=Independent (explained) variable ; X_1=First dependent (explanatory) variable ; X_2 = Second dependent (explanatory) variable ; X_3 = Second dependent (explanatory) variable $ß_o$=Y-intercept parameter indicating the Y value not contributed by X_1, X_2 or X_3. ; $ß_1$ = Slope parameter of the line for X_1 i.e the partial regression coefficient which expresses the absolute value of Y value of X_1; $ß_2$ = Slope parameter of the line for X_2 i.e the partial regression coefficient which expresses the absolute value of Y value of X_2; $ß_3$ = Slope parameter of the line for X_3 i.e the partial regression coefficient which expresses the absolute value of Y value of X_3, ε = Random error. $ß_1$, $ß_2$ and $ß_3$ are partial coefficients reflecting the proportionnal change in the dependent variable Y per unit change in X_1, X_2 and X_3 independent (explanatory) variables. Both models are associated with the model explanatory power, R², called coefficient of determination, ranging from 0 to 1.

In the present study, CEC was considered the dependent variable, while soil pH (X_1), % clay (X_2) and % OC (X_3) were the dependent variables.

3. RESULTS AND DISCUSSION

3.1 Mean Values of dependent (CEC) and independent (pH, % clay, % OC) variables

Results of used data and linear model fitting are consigned in Table 1 to 8. Table 1 indicates soil pH, % Clay, % OC and CEC mean values et their standard deviations for the 4 AEZ under study. Overall means of the 4 soil parameters accross AEZ were also calculated and posted. As a remainder, the total soil sample size was dispatched into : Imbo (34), Kirimiro (73), Moso (83) and Mumirwa (66).

Table 1. Mean % Clay, % Organic C and CEC values of used soil samples

Parameter	Imbo (1)	Kirimiro (2)	Moso (3)	Mumirwa (4)	1+2+3+4
pH	6.67±0.80	5.38±0.57	5.69±0.74	5.32±0.78	5.57±0.84
% Clay	23.57±12.57	45.06±16.97	43.43±20.85	42.94±13.72	41.04±18.10
% OC	1.12±0.56	1.82±1.05	1.45±0.77	2.47±1.22	1.77±1.06
CEC	14.99±13.12	10.70±5.70	10.10±5.23	16.00±8.27	12.36±7.63

Percent clay ranged from 24 % (Imbo) to 45 % (Kirimiro), while % OC was lowest in Imbo (1.12 %) and highest (2.5 %) in Mumirwa. CEC values were as low as 10 $cmole_c$/kg soil (Moso, Kirimiro) to as high as 16 $cmole_c$/kg soil (Mumirwa). Soil pH values were acidic in Mumirwa (5.32), Kirimiro (5.38), Moso (5.69) and near neutral (6.67) in the Imbo AEZ.

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3.2. Simple Linear Regression Models

Simple linear regressions between CEC and soil pH (Table 2), CEC and % OC (Table 3), CEC and % Clay (Table 3) were evaluated. Best significant regression equations were evaluated at 5 % probability level and higher coefficients of determination (R^2).

Table 2. Simple Linear Regression Equations between CEC and pH

AEZ	Equations	Probability	R^2
Imbo	CEC = 20.15(±20.87) – 1.27(±3.13) pH	0.69NS	0.01
Kirimiro	CEC = 6.62(±6.15) + 0.75(±1.131) pH	0.51NS	0.01
Moso	CEC = 5.97(±5.46) + 0.64(±0.98) pH	0.52NS	0.01
Mumirwa	CEC = -2.40(±4.55) + 3.19(±0.84) pH	< 0.0001***	0.21
All data	CEC = 5.26(±3.01) + 1.13(±0.54) pH	< 0.05*	0.02

Table 2 depicts a total absence of the pH effect on CEC accross all Imbo, Kirimiro and Moso AEZ ($p > 0.05$, $R^2 \approx 0$). Regression coefficients were significant for the Mumirwa AEZ ($p < 0.05$) though with a small coefficient of determination (R^2=0.21). When pH data were combined accross the four AEZ, R^2 (=0.02) value did not improve, although the level of probability associated withe linear regression model was significant, reflecting that, in the present study, soil pH is a poor predictor of CEC.

Table 3. Simple Linear Regression Equations between CEC and % OC

AEZ	Equations	Probability	R^2
Imbo	CEC = 3.28(±6.50) + 10.25(±4.91) OC	0.05*	0.20
Kirimiro	CEC = 3.29(±0.88) + 4.07(±0.42) OC	< 0.0001***	0.56
Moso	CEC = 4.59(±1.03) + 3.74(±0.61) OC	< 0.0001***	0.36
Mumirwa	CEC = 5.46(±1.84) + 4.23(±0.66) OC	0.0001***	0.40
All data	CEC = 4.28(±0.79) + 4.12(±0.37) OC	< 0.0001***	0.53

Percent OC appears a better predictor of CEC than soil pH ($p < 0.05$). Causal effects of % OC on CEC as described by the coefficient of determination (R^2) indicate that 56 % of CEC variation in the Kirimiro AEZ could be explained by % OC. A similar effect (53 %) is observed when data are combined. However, lower coefficients of determination (R^2) are observed in Imbo (0.20), Moso (0.36) and Mumirwa (0.40) AEZ.

Table 4. Simple Linear Regression Equations between CEC and % clay

AEZ	Equations	Probability	R^2
Imbo	CEC = 0.40(±0.17) + 0.03(±0.01) Clay	< 0.0001***	0.45
Kirimiro	CEC = 1.00(±1.45) + 0.22(±0.03) Clay	< 0.0001***	0.41
Moso	CEC = 0.91(±0.25) + 0.01(±0.01) Clay	0.017*	0.09
Mumirwa	CEC = 1.18(±0.42) + 0.03(±0.01) Clay	0.004**	0.14
All data	CEC = 3.85(±1.03) + 0.19(±0.02) Clay	< 0.0001***	0.25

Although regression coefficients were significant for all 5 equations ($p < 0.05$), associated coefficients of determination (R^2) were quite lower to nil. Only 40-45 % of the CEC variation is controlled by % clay in Imbo and Kirimiro AEZ. On the other hand, less than 15 % of CEC is controlled by % clay in Moso (9 %) and Mumirwa (14 %) AEZ, while combined data show a statistically significant 25 % causal (but low) effect of % clay on CEC variation.

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3.2 Multiple Linear Regression

When CEC, pH, % OC C and % clay data were subjected to multiple linear regression, Table 5-8 were generated.

Table 5. Multiple Linear Regression Equations between CEC, pH and % clay

AEZ	Equations	R^2
Imbo	CEC = -13.27(±16.44) + 2.54(±2.34) pH + 0.32(±0.08) clay	0.56
Kirimiro	CEC = -1.84(±4.89) + 0.53(±0.87) pH + 0.22(±0.47) clay	0.63
Moso	CEC = -4.75(±4.26) + 1.307(±0.72) pH + 0.17(±0.03) clay	0.42
Mumirwa	CEC = -10.38(±4.48) + 3.27(±0.74) pH + 0.17(±0.04) clay	0.39
All data	CEC = -6.90(±2.77) + 1.91(±0.45) pH + 0.19(±0.02) Clay	0.34

All regression equations between CEC, pH and % clay and were significant at $p < 0.05$. Addition of % clay to pH as explanatory variables of the CEC remarquably improved regression relationships for all AEZ, notably for Kirimiro and Imbo AEZ zones. It is of interest to note that R^2 increased from almost 0 to 0.63 in Kirimiro, 0.56 in Imbo, 0.42 in Moso AEZ and from 0 to $R^2 = 0.34$ when all data are combined. Combining pH to % clay as explanatory dependent variables of CEC slightly improved R^2 from 0.21 to 0.39 in the Mumirwa AEZ.

Table 6. Multiple Linear Regression Equations between CEC, pH and % OC

AEZ	Equations	R^2
Imbo	CEC = -30.82(±16.08) + 4.68(±2.23) pH + 9.91(±1.92) OC	0.66
Kirimiro	CEC = -9.24(±4.12) + 2.24(±0.72) pH + 4.32(±0.41) OC	0.62
Moso	CEC = -3.65(±4.58) + 1.41(±0.78) pH + 3.71(±0.60) OC	0.39
Mumirwa	CEC = -8.80(±3.67) + 3.00(±0.65) pH + 3.09(±0.50) OC	0.53
All data	CEC = -8.67(±2.23) + 2.28(±0.37) pH + 4.17(±0.27) OC	0.55

Combining pH and % OC as explanatory variables of the CEC improved regression relationships in all AEZ ($p < 0.05$), most notably in Imbo and Kirimiro AEZ. Addition of % OC to pH raised R^2 from almost 0 to 0.66 in Imbo, 0.62 in Kirimiro, 0.55 when all data are combined and 0.39 in the Moso AEZ. Combining pH to % clay only improved coefficient of determination R^2 from 0.21 to 0.53 in the Mumirwa AEZ.

Table 7. Multiple linear regression equations between CEC and % clay and % OC

AEZ	Equations	R^2
Imbo	CEC = 1.99(±2.20) + 0.16(±0.09) clay + 4.88(±0.09) OC	0.64
Kirimiro	CEC = 0.19(±1.15) + 0.119(±0.03) clay + 3.09(±0.47) OC	0.63
Moso	CEC = 0.37(±1.02) + 0.13(±0.02) clay + 2.55(±0.50) OC	0.62
Mumirwa	CEC = 4.13(±2.08) + 0.09(±0.05) clay + 2.75(±0.61) OC	0.40
All data	CEC = 1.82(±0.74) + 0.09(±0.02) clay + 3.16(±0.29) OC	0.54

Percent clay and % OC as explanatory variables of CEC showed significant effects ($p < 0.05$) on CEC in all AEZ, notably in Moso where R^2 increased from 0 to 0.62. Similar effect was observed in the Mumirwa AEZ with R^2 increasing from 0.14 with % clay as an explanatory variable alone to 0.40 when % clay is combined with % OC. Combined data from the 4 AEZ doubled R^2 from 0.25 to 0.54. A similar analysis applied to Imbo and Kirimiro AEZ indicated an increase of R^2 values from ≈0.4 to slightly over 0.6.

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Table 8. Multiple linear regression equations between CEC, pH, % clay and % OC

AEZ	Equations	R^2
Imbo	CEC = -33.19(±14.14)+4.91(±1.96) pH+0.17(±0.07) clay+6.89(±2.14) OC	0.76
Kirimiro	CEC = -9.67(±3.85)+1.83(±0.68) pH+0.10(±0.03) clay+3.41(±0.46) OC	0.67
Moso	CEC = -9.68(±3.54)+1.73(±0.59) pH+0.13(±0.02) clay+2.72(±0.47) OC	0.66
Mumirwa	CEC = -12.49(±3.74)+3.08(±0.61) pH+0.10(±0.04) clay+2.59(±0.51) OC	0.59
All data	CEC = -13.12(±2.11)+2.52(±0.34) pH+0.11(±0.02) clay+3.43(±0.26) OC	0.64

As for the previous regression equations, regression coefficients were all significant ($p < 0.05$) accross AEZ as well as when data were combined. The highest regression fit as shown by coefficient of determination was obtained in Imbo AEZ (R^2=0.76). All other regresson equations were characterized by R^2 values ranging from 0.59 (Mumirwa) to 0.67 (Kirimiro).

An close analytical view performed accross our regression results highlights that regression coefficients of determination or else model explanatory power followed the order : Imbo (R^2 = 0.76) > Kirimiro (R^2 = 0.67) > Moso (R^2 = 0.66) > all AEZ data combined (R^2 = 0.59) > Mumirwa (R^2 = 0.59). The second best regression equations were observed with two different explanatory variables combinations : % clay and % OC in Imbo AEZ (R^2 = 0.66) ; pH and % clay or % clay and % OC in Kirimiro AEZ (R^2 = 0.63) ; % clay and % OC in Moso AEZ (R^2 = 0.62) ; pH and % OC in Mumirwa AEZ (R^2 = 0.53), and pH and % OC, when all data are combined (R^2 = 0.55).

Comparisons of our findings show coherence with other investigators. In New Zealand, Parfitt et al., 1995 [17] reported an increase in CEC with inceasing organic matter and observed a positive interaction between clay and organic matter (organic C). Similar observations were advanced by Manrique et al., 1991 [3] who considered % OC and % clay as good alternatives to predict CEC. In some other instances, CEC from clay and OM increases with increasing pH [12].

Some investigators found and reported various effects of horizons. In an old study reported by Wilding and Rutledge (1966) [18], organic matter contributed most of CEC in A horizons whereas clay (< 0,2 µ) contributed most of it in B horizons. Similar observations were advanced by the work of Wright and Foss (1972) [20] and Martel et al. (1978) [27]. These investigators found and reported that multiple regression analysis indicated that organic matter (organic C) is a better predictor of CEC of surface horizons and % clay in deeper horizons, although its contribution is controlled by its degree of decomposition, as well as its amount present in the soil [9].

Findings of Seybold and Grossman (2006) [13, 15] indicated that in oxisols similar to soils used in our study, pH and % OC are often weak predictors of CEC. Poor relationships were also reported in Alfisol presumably due to other sources of CEC or variability in clay mineralogy, organic matter composition or both [28]. Variation of CEC might be due to the type of mineral present in the soil, an example being the presence of kaolinite typical of highly weathered soils (Alfisols, Ultisols, Oxisols, Inceptisols) of the tropics [9], which include Burundi high altitude soils [20].

As was observed elsewhere [3], among soil pH, % clay and % OC, the last two dependent variables of CEC are key determinants of CEC. In their study, the above mentionned investigators reported that % clay + % OC + soil pH control 51 % of CEC variation. Percent clay + % OC control 67 % of CEC in Alfisol, Inceptisol, Mollisol and Vertisol, and 78 % in Entisol. In Philippine soils, [19] indicated that organic matter contributed to 37.6 % variation of the CEC for 62.4 % from clay. Their combination contributed to 60 % of the CEC variation. In New Jersey (temperate) soils, CEC variation was controlled at 59 % by % clay and organic matter [28]. In some other cases [17], % OC was found to be the most important determinant factor of soil CEC (CEC = 7.93 + 8.72 OC with R^2 = 0.74). Similar findings showed that CEC was explained at 96 % by % clay, % organic C and pH [29] or at 90 % by % silt, % clay, % OC and pH [30].

4. CONCLUSION

A statistical linear regression study was performed on surface soil samples collected in four Burundi agro-écological zones (AEZ) to evaluate the causal effects of soil pH, % clay and % C on CEC. The four AEZ, which represent 40 % of the country total land were : Imbo, Mumirwa, Kirimiro and Moso. Simple, two-way and 3-way linear regression models

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were evaluated on individual and combined AEZ soil data. The global analysis of the study findings show the results shared hereafter. Soil pH did not show any statistical effect on CEC in all cases. Effect of % clay as a explanatory variable of CEC was characterized by smal coefficient of determination (R^2=0.25-0.45). Similar value was as high as R^2=0.5-0.6 when % OC was the explanatory variable of CEC. In 2-way regression analyses, the following determination coefficients were obtained : pH and % clay (R^2=0,40 (Mumirwa) - 0,63 (Kirimiro) ; pH and % OC (R^2=0.40 (Moso) – 0.66 (Imbo) ; % clay and % OC (R^2=0.40 (Mumirwa) – 0.60 (Imbo, Kirimiro). The 3-way (pH, % clay and % OC) regression analysis gave statistically significant higher R^2 values, ranging from 0.60 (Mumirwa) to 0.76 (Imbo). Moreover, even when the linear regression analysis was performed on pooled data, the outcome was the same, in that the 3-way combination of soil pH, % clay and % OC showed the best fit (R^2=0,64). All in all, consistently with other investigators, our results stress that % OC emerges as the key determinant and predictor of CEC in highly weathered, kaolinitic rich tropical soils, such as most Burundi soils. This observation rightly highlights the key additive value of % OC in the improvement and management of tropical soil chemical quality, as was demonstrated elsewhere in Burundi [31].

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