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Study on Exchangeable Cation Determining Base Saturation Percentage of Soil in South China

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Abstract

Base saturation percentage (BSP) is an important soil chemical index in soil fertility and soil taxonomy. However, it is still unclear what exchangeable cation dominates BSP of soil in south China. Therefore, in this study, the data of BSPs and exchangeable H^+, Al^{3+}, Ca^{2+}, Mg^{2+}, K^+ and Na^+ of 109 and 45 horizon samples of 50 and 28 soil species in red soil and yellow soil groups in the Database of Chinese Soil Species were used to explore further the characteristics of BSPs and exchangeable cations as well as the correlation between BSPs and exchangeable cations. The results showed that the concentrations of exchangeable cations in both red soil and yellow soil groups were in an order of Al^{3+} (4.55 ± 1.47 and 4.22 ± 1.2 cmol(+)/kg) > Ca^{2+} (0.32 ± 0.21 and 0.36 ± 0.24 cmol(+)/kg) > H^+ (0.23 ± 0.13 and 0.19 ± 0.10 cmol(+)/kg) > K^+ (0.16 ± 0.09 and 0.16 ± 0.11 cmol(+)/kg) > Mg^{2+} (0.13 ± 0.09 and 0.11 ± 0.08 cmol(+)/kg) > Na^+ (0.08 ± 0.06 and 0.11 ± 0.06 cmol(+)/kg). For red soil group, Al^{3+} concentration was significantly higher than those of other exchangeable cations, Ca^{2+} and H^+ concentrations were significantly higher than those of K^+, Mg^{2+} and Na^+; while for yellow soil group, Ca^{2+}, H^+ and K^+ concentrations were significantly higher than those of Mg^{2+} and K^+. BSP of red soil group was codetermined by Ca^{2+}, Al^{3+}, Mg^{2+} and Na^+, with the contributions of 33.81%, 19.82% and 14.49%, respectively; while BSP of yellow soil group was codetermined by Al^{3+}, Ca^{2+}, Mg^{2+}, K^+ and Na^+, with the contributions of 24.91%, 21.55%, 19.91% and 14.21%, respectively. A higher concentration of exchangeable cation does not mean the higher importance of the cation to soil BSP.

Keywords

Base Saturation Percentage (BSP), Exchangeable Cations, Correlation, Red Soil, Yellow Soil, South China

1. Introduction

Base saturation percentage (BSP) is an important soil chemical index which has implication not only in soil fertility [1] [2] [3] but also in soil taxonomy [4] [5]. Existing studies have pointed out that BSP could be affected by climatic, geochemical, and environmental conditions, such as acid rain and dust deposition, waterlogging condition, pH, nitrogen application, organic matter and clay contents, cation exchange capacity and so on [6], but these studied factors mainly are external or indirect factors. As defined as the sum of exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} relative to total soil cation exchange capacity (CEC) at pH 7.0 or 8.2 [7] [8], BSP is conceptually affected simultaneously by Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Al^{3+} and H^{+}. Some studies found that BSP was dominated by Ca^{2+} for the calcareous soils on a small orchard scale [9] [10], but no consideration was given to the importance of different exchangeable cations to BSPs.

Red soil and yellow soil groups (in Chinese Genetic Classification) are two important zonal soil groups widely distributed in the hilly area of tropical and subtropical south China which are characterized by high desilicification but fersialitization [11] [12]. There are 133 and 76 soil species in red soil and yellow soil groups, respectively, which were derived under diverse climate conditions, parent materials and land use types [13]. However, it is still unclear that what exchangeable cations dominate BSPs of red soil and yellow soil groups; therefore, the objective of our study is to understand further the characteristics of BSPs and exchangeable cations, and to quantitatively analyze the importance of different exchangeable cations to BSPs of red soil and yellow soil groups.

2. Methods and Materials

2.1. Data Sources

The data of BSPs and exchangeable cation concentrations (H^{+}, Al^{3+}, Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) are from Chinese Soil Database (http://vdb3.soil.csdb.cn/). After the comparison of data completeness and the elimination of abnormal data by the method of $\mu \pm 3\sigma$, 136 and 58 horizon samples from 59 and 28 soil species in red soil and yellow soil groups in South China were adopted, respectively (see **Figure 1**), here, the spatial location of the selected soil species in Figure were roughly determined according to the information of site description of the typical soil profiles in the available literatures [13]. Other main soil groups such as latosol and latosolic red soil groups were not considered due to the insufficient typical profiles (less than 8 soil profiles) after the elimination of abnormal data of BSPs and exchangeable cations.

2.2. Sampling and Measurement of Soil Samples

According to the available historical records, the sampling and measurement of soil samples were as follows: 1) the location of each typical soil profile was mainly decided by the comprehensive consideration of the representation of topography, parent material, land use type, and etc.; 2) a standard soil profile

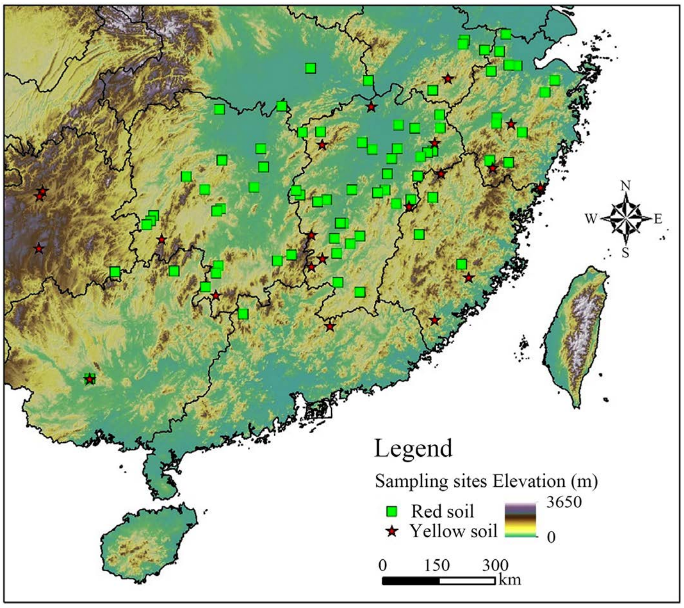

Figure 1. Spatial distribution of adopted soil profiles of red soil and yellow soil groups.

(1.0 m in width and 1.2 - 1.5 m in depth) was excavated; 3) the horizons were decided according to morphological characteristics of profile; 4) soil sample was collected uniformly within each horizon, and 2 kg of soil was kept left by using quartering and kept in the cloth bag. In the lab, soil samples were air dried, and the impurities of roots and gravels were removed. Then they were grinded to pass 1.7 mm, 0.25 mm and 0.149 mm sieves respectively.

Exchangeable K^+ and Na^+ were determined by flame photometer method, Ca^{2+} and Mg^{2+} determined by the method of EDTA volumetric method, H^+ and Al^{3+} were determined by titration method after 1 mol/L KCl extraction, total amount of base exchangeable cations determined by the method of evaporation and neutralization titration after 1 mol/L NH_4OAc (pH 7.0) extraction, cation exchange capacity (CEC) determined by the method of 1 mol/L NH_4OAc exchange [8] [14] [15].

2.3. Data Processing, Modeling and Mapping

Microsoft Excel 2016 and IBM Statistics SPSS 20.0 were used for data processing, correlation modeling and mapping, difference significance of exchangeable cations and BSPs were tested by LSD method of one-way ANOVA, Pearson correlation (2-tailed) was used to describe the correlation between exchangeable cations and BSP [16] [17]. The contributions of exchangeable cations to BSP is calculated as follows: by using SPSS, the data of exchangeable cations and BSP were normalized, the multiple linear regression model between BSP and exchangeable cations was obtained, and then the percentage of the coefficient of *i* cation to total sum of the coefficients of all exchangeable cations in the model was calculated as the contribution of *i* cation to BSP [18]. Here, principle component analysis was not used to do so is because we want to quantitatively know the contribution of each cation to BSP.

3. Results and Discussions

3.1. Statistical Information of Exchangeable Cations and BSPs

Table 1 gives the statistical information of exchangeable cations and BSPs of red soil and yellow soil groups. It can be seen from Table 1 that except Na^+, there were no significant differences in other exchangeable cations between red soil and yellow soil groups ($p < 0.05$). BSP of yellow soil group was significantly higher than that of red soil group ($p < 0.05$). cation concentrations of both red soil and yellow soil groups were in an order of $Al^{3+} > Ca^{2+} > H^+ > K^+ > Mg^{2+} > Na^+$, in which Al^{3+} was significantly higher than all other exchangeable cations. For red soil group, Ca^{2+} and H^+ were significantly higher than K^+, Mg^{2+} and Na^+, but no significant difference between Mg^{2+}, K^+ and Na^+. For yellow soil group, Ca^{2+} was significantly higher than Mg^{2+}, K^+ and Na^+, but no significant difference between H^+, Mg^{2+}, K^+ and Na^+. 4) All exchangeable cations and BSPs of red soil and yellow soil groups were in moderate variation (coefficient of variation < 100%) and in positive skew distribution (skewness > 0), while their probability density curves of all exchangeable cations and BSPs were near very flat (kurtosis = 0) or flat (0 < kurtosis < 0.67) [16] [17].

3.2. Correlations between BSPs and Exchangeable Cations

For the correlation between BSP with exchangeable cations, it can be seen from Table 2 that, 1) for red soil group, BSP had notable correlation (R = 0.5 - 0.8, the same below) with Ca^{2+}, Mg^{2+} and Al^{3+} while low correlation (R = 0.3 - 0.5, the same below) with Na^+ for red soil group; 2) for yellow soil group, BSP had notable correlation with Ca^{2+} and Al^{3+} while low correlation with Na^+, Mg^{2+} and K^+; 3) low correlation were found between H^+ with Al^{3+}, Ca^{2+} with Mg^{2+} and Na^+ in both soil groups and between Mg^{2+} with K^+ and Na^+ in yellow soil group.

Table 1. Statistical information of exchangeable cations and BSPs of red soil and yellow soil groups.

Ion	Red soil group (n = 109)				Yellow soil group (n = 45)			
	Mean ± Std.D	C.V. (%)	Skewness	Kurtosis	Mean ± Std.D	C.V. (%)	Skewness	Kurtosis
H^+	0.23 ± 0.13b	58.44	0.71	−0.38	0.19 ± 0.10bc	52.58	0.37	−0.79
Al^{3+}	4.55 ± 1.47a	32.26	0.53	0.46	4.22 ± 1.24a	29.35	0.20	−0.46
Ca^{2+}	0.32 ± 0.21b	65.63	0.93	0.27	0.36 ± 0.24b	66.28	0.92	0.11
Mg^{2+}	0.13 ± 0.09c	68.12	0.64	−0.28	0.11 ± 0.08c	68.12	0.59	0.06
K^+	0.16 ± 0.09c	56.85	0.83	0.42	0.16 ± 0.11c	65.78	0.37	−0.97
Na^+	0.08 ± 0.06c	79.53	0.63	−0.46	0.11 ± 0.06c	54.23	0.82	−0.33
BSP	13.26 ± 5.85B	44.16	0.30	−0.81	16.03 ± 7.87A	49.11	0.40	−0.40

*. Different lowercase letters in the same columns show mean difference of exchangeable cations is significant at the 0.05 level, and different capital letters in BSP line show mean difference of BSPs is significant at the 0.05 level.

Table 2. Pearson correlation coefficients (R) between exchangeable cations and BSPs.

Soil group	Parameter	H^+	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	Na^+
Red soil (n = 109)	H^+	1					
	Al^{3+}	0.219^{*}	1				
	Ca^{2+}	0.081	0.002	1			
	Mg^{2+}	0.046	0.043	0.420^{**}	1		
	K^+	0.164	0.120	0.062	0.310^{**}	1	
	Na^+	0.104	0.019	0.364^{**}	0.314^{**}	−0.095	1
	BSP	−0.074	**-0.504^{**}**	**0.668^{**}**	**0.555^{**}**	0.170	0.455^{**}
Yellow soil (n = 45)	H^+	1					
	Al^{3+}	0.351^{**}	1				
	Ca^{2+}	0.073	0.028	1			
	Mg^{2+}	−0.119	0.024	0.305^{*}	1		
	K^+	0.147	−0.007	0.222	0.079	1	
	Na^+	−0.057	−0.149	0.408^{**}	0.125	0.076	1
	BSP	−0.221	**-0.526^{**}**	**0.598^{**}**	0.457^{**}	0.300^{*}	0.461^{**}

** and * Correlation are significant at the 0.01 and 0.05 levels (2-tailed).

Table 3 lists the optimal correlation models between BSPs with exchangeable cations and the multiple linear regression models between BSPs and exchangeable cations, it shows that most of the optimal models are in a quadratic pattern.

Table 4 shows the calculated importance of exchangeable cations to BSPs with the Random Forest Package, it can be seen from Table 4 that, 1) the importance of H^+ and K^+ of red soil were not significant to BSP, while only that of H^+ not significant for yellow soil; 2) the orders of BSPs and the importance of the top three exchangeable cations to BSPs were different between red soil and yellow soil groups, which was Ca^{2+} (33.81%) > Al^{3+} (29.87%) > Mg^{2+} (22.28%) for red soil, while Al^{3+} (24.91%) > Ca^{2+} (21.55%) > Mg^{2+} (19.91%) for yellow soil; 3) although generally the importance of Ca^{2+}, Al^{3+} and Mg^{2+} to soil BSPs are greater due to their high concentrations, no significant correlation was found between cation concentrations and their importance to BSPs if all exchangeable cations are considered.

3.3. Discussion

Some studies already proved and explained that Al^{3+} was the main form in exchangeable acid exchangeable cations in soils of south China [19] [20] [21] [22]. Our data also showed Al^{3+} were the highest in all exchangeable cations both in red soil and yellow soil groups, which is common in soils of south China due to intensive desilicification but fersialitization caused by high temperature and precipitation [11] [12] [13], so it is normal for Al^{3+} as one of the important exchangeable cations controlling BSPs of red soil and yellow soil groups in south China.

Table 3. Optimal correlation models between BSPs with exchangeable cations of red soil and yellow soil groups.

Soil group	Optimal model
Red soil (n = 109)	BSP (%) = $-1.624\text{Al} + 20.628$ R = -504^*, $p < 0.01$
	BSP (%) = $-15.682\text{Ca}^2 + 31.098\text{Ca} + 5.487$ R = 0.668^{**}, $p < 0.01$
	BSP (%) = $-21.439\text{Mg}^2 + 43.807\text{Mg} + 8.059$ R = 0.555^{**}, $p < 0.01$
	BSP (%) = $-240.86\text{Na}^2 + 101.16\text{Na} + 8.010$ R = 0.455^{**}, $p < 0.01$
	BSP (%) = $14.408 - 2.082\text{Al}^{3+} + 12.698\text{Ca}^{2+} + 21.475\text{Mg}^{+} + 17.710\text{Na}^{+}$, R = 0.916^{**}, $P < 0.01$,
Yellow soil (n = 45)	BSP (%) = $0.296\text{Al}^2 - 5.327\text{Al} + 32.762$ R = -0.526^{**}, $p < 0.01$
	BSP (%) = $-16.189\text{Ca}^2 + 33.165\text{Ca} + 6.613$ R = 0.598^{**}, $p < 0.01$
	BSP (%) = $17.292\text{Mg}^2 + 33.264\text{Mg} + 11.166$ R = 0.457^{**}, $p < 0.01$
	BSP (%) = $25.933\text{K}^{0.306}$ R = 0.300^*, $p < 0.05$
	BSP (%) = $-414.68\text{Na}^2 + 163.66\text{Na} + 4.4735$ R = 0.461^{**}, $p < 0.01$
	BSP (%) = $15.298 - 2.636\text{Al}^{3+} + 12.271\text{Ca}^{2+} + 26.041\text{Mg}^{+} + 11.729\text{K}^{+} + 20.603\text{Na}^{+}$, R = 0.888^{**}, $P < 0.01$

Table 4. Importance of exchangeable cations to BSPs in red soil and yellow soil groups.

Red soil group				Yellow soil group			
Cation	Importance	Norm. importance	Sig.	Cation	Importance	Norm. importance	Cation
Ca^{2+}	38.00	33.81	0.02^*	Al^{3+}	18.47	24.91	0.02^*
Al^{3+}	29.87	26.58	0.02^*	Ca^{2+}	15.98	21.55	0.02^*
Mg^{2+}	22.28	19.82	0.02^*	Mg^{2+}	14.76	19.91	0.02^*
Na^{+}	16.28	14.49	0.02^*	K^{+}	10.56	14.24	0.04^*
K^{+}	3.03	2.70	0.29	Na^{+}	10.54	14.21	0.02^*
H^{+}	2.93	2.61	0.21	H^{+}	3.84	5.18	0.18

* Importance is significant at 0.05 level; Norm. means normalized.

The lower concentrations of base exchangeable cations compared with Al^{3+} could be attributed to the heavy leaching losses of base exchangeable cations, which were higher than 80% [23] [24], due to the high temperature and precipitation in south China (annual temperature and precipitation as 16˚C - 25˚C and 800 - 2000 mm, dryness less than 1.0).

A significant difference was found in BSPs between red soil group and yellow soil groups, which could be attributed to the accumulation effects in the differences of the sums of acid exchangeable cations and base exchangeable cations between the two soil groups. It could be found that although there was significant difference in exchangeable cations, the sums of acid exchangeable cations and base exchangeable cations, the sum of acid exchangeable cations of red soil (4.77 ± 1.50 cmol(+)/kg) was higher than that of yellow soil group (4.41 ± 1.27 cmol(+)/kg), while the sum of base exchangeable cations of red soil group (0.69 ± 0.32 cmol(+)/kg) was lower than that of yellow soil group (0.74 ± 0.35

cmol(+)/kg). Generally speaking, red soil group was formed and evolved in the environment with higher temperature and precipitation (15˚C - 25˚C in annual mean temperature and 1200 - 2500 mm in annual precipitation) compared to yellow soil group (14˚C - 19˚C in annual mean temperature and 1000 - 2000 mm in annual precipitation), which resulted in higher acid exchangeable cations and lower base exchangeable cations of red soil group compared with yellow soil group [11] [12] [13].

Some studies found that BSP was dominated by Ca^{2+} in calcareous soil species on a small orchard scale due to the highest concentration of Ca^{2+} derived from the calcareous parent material [9] [10], but didn't give information on the importance of exchangeable cations to BSPs. In contrast, our study not only found further that cation concentrations were in order of $Al^{3+} > Ca^{2+} > H^+ > K^+ > Mg^{2+} > Na^+$ both in red soil and yellow soil groups (see **Table 1**), but also disclosed the importance of exchangeable cations to BSPs, for examples, the importance order of exchangeable cations to BSPs were Ca^{2+} (33.81%) > Al^{3+} (26.58%) > Mg^{2+} (19.82%) > Na^+ (14.49%) > K^+ (2.70%) > H^+ (2.61%) for red soil group while Al^{3+} (24.91%) > Ca^{2+} (21.55%) > Mg^{2+} (19.91%) > K^+ (14.24%) > Na^+ (14.21%) > H^+ (5.18%) for yellow soil group. However, our study shows that exchangeable cations controlling BSPs are different between red soil and yellow soil groups, we think such a complexity is normal because our study includes 59 and 28 soil species of red soil and yellow groups, respectively, which are widely distributed in south China with various soil forming environments and evolution degrees [11] [12] [13]. For examples, the spans of annual temperature and precipitation were 15˚C - 25˚C and 1200 - 2500 mm for red soil while 14˚C - 19˚C and 1000 - 2000 for yellow soil, respectively [11] [12], meanwhile, the parent materials include granite, sandstone, quaternary red clay, pelite, quartzite, tuff, basalt, shallow-sea sediment, andesite and limestone, etc. and the land use types include dryland, forest, orchard, shrub, grassland, etc. (see **Table 5** and **Table 6**, only main parent materials and land use types presented in the tables),

Table 5. Statistical information of exchangeable cations concentrations and BSPs of soils derived from different parent materials.

Cation	Granite (n = 51)	Sandstone (n = 38)	Q_4 red clay (n = 22)	Pelite (n = 22)	Quartzite (n = 21)
H^+	0.20 ± 0.11bc	0.22 ± 0.13ab	0.20 ± 0.14ab	0.27 ± 0.14a	0.22 ± 0.10ab
Al^{3+}	4.65 ± 1.44ab	4.45 ± 1.66ab	4.95 ± 1.13a	3.96 ± 1.06bc	3.99 ± 1.23bc
Ca^{2+}	0.30 ± 0.22a	0.36 ± 0.21a	0.37 ± 0.26a	0.32 ± 0.23a	0.36 ± 0.20a
Mg^{2+}	0.13 ± 0.08a	0.12 ± 0.09a	0.12 ± 0.10a	0.14 ± 0.08a	0.12 ± 0.09a
K^+	0.20 ± 0.10a	0.10 ± 0.05c	0.15 ± 0.08b	0.21 ± 0.09a	0.12 ± 0.08bc
Na^+	0.09 ± 0.06a	0.12 ± 0.07a	0.07 ± 0.06b	0.07 ± 0.04b	0.09 ± 0.06a
BSP (%)	14.10 ± 7.07a	13.54 ± 6.02a	12.49 ± 4.72a	15.44 ± 6.92a	15.17 ± 7.83a

*. Different lowercase letters in the same lines show mean difference is significant at the 0.05 level. Not included soil species with unclear information in parent materials or with the less numbers of profiles.

Table 6. Statistical information of exchangeable cations concentrations and BSPs of soils under different land use types.

Cation	Dryland (n = 30)	Forest (n = 103)	Orchard (n = 7)	Shrub&grass (n = 7)
H^+	0.21 ± 0.13a	0.22 ± 0.12a	0.18 ± 0.10a	0.24 ± 0.15a
Al^{3+}	4.12 ± 1.59c	4.41 ± 1.36c	4.57 ± 1.00ab	5.43 ± 1.23a
Ca^{2+}	0.30 ± 0.21b	0.32 ± 0.22b	0.52 ± 0.27a	0.47 ± 0.18a
Mg^{2+}	0.15 ± 0.09a	0.12 ± 0.08a	0.15 ± 0.07a	0.11 ± 0.10a
K^+	0.13 ± 0.08bc	0.17 ± 0.09a	0.21 ± 0.13a	0.13 ± 0.10ab
Na^+	0.10 ± 0.07b	0.08 ± 0.06b	0.05 ± 0.03b	0.15 ± 0.07a
BSP (%)	14.68 ± 7.09a	13.80 ± 6.82a	16.32 ± 2.78a	13.59 ± 5.33a

*. Different lowercase letters in the same lines show mean difference is significant at the 0.05 level. Soil species with unclear information in land use types were omitted in this study.

and it can be seen from Table 5 and Table 6 that Al^{3+}, Ca^{2+} and H^+ are the top three exchangeable cations in concentrations not only in different parent materials but also in different land use types, and there are certain differences in cation concentrations but no significant difference in BSPs between different parent materials or different land use types.

However, there are still some problems left to be solved in our study, for examples, why H^+ is not significantly important to BSP with a higher concentration than K^+, Mg^{2+} and Na^+? Why K^+ is significantly important to BSP of yellow soil group but not to red soil group?

4. Conclusion

By using the data of BSPs and cation concentrations of soil species of red soil and yellow soil groups in south China, our study disclosed that the concentrations of exchangeable cations in both red soil and yellow soil groups were in an order of $Al^{3+} > Ca^{2+} > H^+ > K^+ > Mg^{2+} > Na^+$. BSP of red soil group was codetermined by Ca^{2+}, Al^{3+}, Mg^{2+} and Na^+, while BSP of yellow soil group by Al^{3+}, Ca^{2+}, Mg^{2+}, K^+ and Na^+. But no significant correlation was found between cation concentration and importance of cation to soil BSP if all exchangeable cations are considered.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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