CSIRO Publishing

Australian *Journal* of Soil Research

VOLUME 39, 2001

An international journal for the publication of original research into all aspects of soil science

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Aust. J. Soil Res., 2001, **39**, 991–1001

Changes in the surface charge characteristics of degraded soils in the wet tropics through the addition of beneficiated bentonite

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Abstract

In their pristine state, soils of the wet tropics maintain highly productive climax rainforests that have an intrinsically tight nutrient cycling capacity. When these ecosystems are disturbed and placed under agronomic production, soil organic matter is rapidly lost due to continuous stirring of surface soils, and consequently, there is a rapid decline in fertility. In this study a methodology is presented that quantifies the degree of degradation that an agronomic system has undergone since land conversion. In an effort to reverse this degradation, a glasshouse study was undertaken to evaluate the effect of applying beneficiated bentonite clays on the surface charge characteristics of 2 degraded soils and their influence on the growth of sorghum.

The properties of an Oxisol cleared of climax rain forest 53 years previously and currently under tea production were compared with an adjacent undisturbed forest. Soil pH declined by approximately 0.6 unit. Organic carbon levels decreased dramatically under the disturbed site, along with exchangeable basic cations. The degree of degradation associated with changed land use was estimated to be 85% for the surface soil horizon.

In an effort to remediate the aforementioned degraded Oxisol and a similarly degraded light-textured Ultisol currently under sugarcane, varying rates (0–40 t/ha) of beneficiated (Ca^{2+}, Mg^{2+}, and K^+ saturated in a ratio of 8 : 4 : 1) bentonite were applied. Charge fingerprints were produced for each treatment prior to and after the growing of a sorghum crop. The basic cation exchange capacity at soil pH was increased from 1.15 to 3.00 $cmol_c$/kg on a light-textured Ultisol and from 0.8 to 2.00 $cmol_c$/kg on the Oxisol through the addition of beneficiated bentonites. This increase in surface charge was found to be permanent. Concomitant with the improved charge characteristics was a significant and sustained increase in forage sorghum biomass production with increasing additions of bentonites on both soil types. The cumulative increase in yield between the control and 40 t/ha bentonite application was a 7.7- and 3.1-fold increase for the Ultisol and Oxisol soil types, respectively.

Additional keywords: soil degradation, charge fingerprint, remediation, benonite clay.

Introduction

In their pristine state, soils of the wet tropics maintain highly productive climax rainforests that have an intrinsically tight nutrient cycling capacity. Soil organic matter (SOM) that effectively acts as a slow release nutrient source mediates this cycling. When these ecosystems are disturbed and placed under agronomic production, SOM is rapidly lost due to continuous mixing of surface soils and consequently, there is a rapid decline in fertility (Gillman *et al.* 1985; Gillman and Abel 1986; Plamondon *et al.* 1991; Aweto *et al.* 1992; Willett 1995). This decline is associated with a reduction in the cation exchange capacity (CEC) thereby limiting the ability of the soil to hold nutrients such as Ca^{2+}, Mg^{2+}, and K^+, which are rapidly lost through leaching. Consequently, most of the crop production systems require significant amounts of inorganic fertilisers to sustain economic yields, and apart

10.1071/SR00063 0004-9573/01/050991

from liming materials, which are only partly intended for fertilisation, there is currently no attempt at soil remediation to a level commensurate with that prior to land conversion.

The restoration of soil organic matter to levels prior to land clearing would reverse some of the aforementioned problems associated with land conversion to agronomic production. However, this is not easily attained, particularly in tropical and subtropical regions, where soils are regularly cultivated. Alternative strategies such as the application of crushed basalt rock, zeolites, and other geological materials have been tested with varying degrees of success (Gillman 1980; Chesworth *et al.* 1987). In this respect the CEC is permanently increased with a concomitant increase in basic cations.

The impact of changed land use on charge characteristics is encapsulated in the charge fingerprint as described by Gillman and Sumpter (1986). This technique provides an assessment of the negative charge characteristics of a soil over the range of pH values that has agronomic significance. It is therefore able to distinguish that portion of the CEC that has the ability to retain basic cations, and predicts changes in CEC as soil solution pH and ionic strength are varied. In addition, it allows an estimation to be made of permanent and variable charge, the influence of components such as organic matter on surface charge expression, and the effects on surface charge associated with anthropogenic disturbance. In the current study, our interest is focussed on the quantification of the changes in surface charge characteristics associated with changed land management. Consequently, when used in conjunction with exchangeable cations extracted from the exchange complex, an assessment of the current and potential cation holding capacity and the impact of applied management strategies can be objectively assessed.

In this study the degree of degradation that a system has undergone due to changed land use is quantified using the concept of the charge fingerprint (Gillman and Sumpter 1986; Menzies and Gillman 1997). Through the construction of charge fingerprints a saturation index (S_u) is calculated with respect to base cation content and an estimation of the degree of degradation that the system has undergone is established. In addition, the remediation of this chemical degradation and its associated productivity is demonstrated in 2 contrasting soil types through the addition of beneficiated bentonite.

Materials and methods

Quantification of the degree of degradation

Site description

The undisturbed site was situated in the wet tropics of north Queensland, Australia, and consisted of a climax tropical rainforest in Wooroonooran National Park (17°37′S, 145°48′E). Adjacent to this forest site and separated by a fence was a tea plantation that had been under agronomic production since 1945. This is referred to as the disturbed site. Since clearing in 1945 the disturbed site had been used for dairy and beef production before being converted to sugarcane production in 1979. From 1985 to present the site has been used for tea production. The soil was classified as a Humic Rhodic Hapludox (Soil Survey Staff 1990). The mean annual precipitation for this area is 3600 mm with a peak occurring in the summer month of February. A paired site approach was used to quantify differences in soil chemical characteristics between the pristine forest site (undisturbed) and adjacent tea (disturbed) plantation.

The selection of the Oxisol site was based on the following criteria: (*i*) the existence of an undisturbed forest in close proximity to an agricultural production field of known history with respect to the period under production; (*ii*) a well-defined boundary separating the 2 land use systems; (*iii*) the same soil type in both areas; and (*iv*) few topographical differences (i.e. slope) between the 2 areas. Soil samples were collected during the dry season in September 1999 by hand auguring at 5 points in each of the sites (disturbed and undisturbed) along a transect at right angles to the boundary separating the 2 land use systems. Sampling points were 5 m apart and samples were collected from the depth intervals 0–10, 10–20, 20–30, 30–50, and 50–70 cm.

A second degraded soil (0–20 cm) was collected from the Herbert River District of north Queensland, which had been under sugarcane production for the past 60 years. This site did not have an equivalent undisturbed site and therefore a paired site analysis could not be undertaken as previously described. The soil was a light-textured sandy Ultisol with a pH_w of 4.69, organic carbon content of 1.07%, and exchangeable Ca^{2+}, Mg^{2+}, K^+, and exchangeable acidity levels of 0.94, 0.27, 0.19, and 1.42 $cmol_c/kg$, respectively.

Soil analyses

Soils samples collected from the Oxisol site were air-dried and sieved through a 2-mm mesh before pH_w was measured in water using a 1 : 5 soil : solution ratio. Basic exchangeable cations were determined by atomic absorption spectrometry after replacement with 0.1 M $BaCl_2/NH_4Cl$ as recommended by Gillman and Sumpter (1986). Acidic cations ($H^+ + Al^{3+}$) were extracted with 1 M KCl and the extractant titrated to pH 8.0 as described by Rayment and Higginson (1992). The effective cation exchange capacity (ECEC) was calculated as the sum of basic and acidic cations ($Ca^{2+} + Mg^{2+} + K^+ + Na^+ + Al^{3+} + H^+$). Soil organic carbon was determined by wet oxidation using the Walkley and Black method as modified by Rayment and Higginson (1992).

Charge fingerprints, which are curves describing the total cation exchange capacity (CEC_T) and base cation exchange capacity (CEC_B) across a range of pH values were determined on composite samples for the depth intervals 0–10, 20–30, and 50–70 cm on both the disturbed and undisturbed samples using the methodology described by Gillman and Sumpter (1986). CEC_B is a measure of the maximum amount of exchangeable basic cations that can be retained in exchangeable form and is, therefore, of agricultural significance. In brief, soils were Ca^{2+} saturated and brought to equilibrium in a 0.002 M $CaCl_2$ matrix. Suspension pH was adjusted to 6 values ranging from approximately 4.0 to 7.5 and exchangeable Ca^{2+} and Al^{3+} displaced with NH_4NO_3. The Al^{3+} content in solution was determined using the pyrocatechol-violet method (Bartlett *et al.* 1987). Amounts of Ca^{2+} and Al^{3+} adsorbed were calculated taking into account the amounts present in the entrained solutes. The CEC_B is operationally defined as the Ca^{2+} adsorbed and CEC_T as the Ca^{2+} and Al^{3+} adsorbed.

Preparation of saturated bentonite

Commercially available sodium-saturated bentonite with a CEC of 51.9 $cmol_c/kg$ was oven-dried at 60°C for 16 h and then ground to a fine powder. Dried and powdered bentonite was weighed (50 g) and added slowly with constant stirring to 2 L of 1 M $CaCl_2$. The slurry was allowed to equilibrate for 4 h with intermittent stirring. After 4 h, the clay suspension was allowed to settle to the bottom of the container. Excess $CaCl_2$ solution was siphoned off and 2 L of distilled water was added and stirred vigorously in order to wash the clay free of excess salts. The entire contents were transferred to polyethylene centrifuge tubes and centrifuged at 2000 rpm for 10 min. This process was repeated until there was evidence of clay dispersion after centrifugation, indicating that the ionic strength of the solution had decreased sufficiently to a level where there was little soluble salt. The slurry containing the Ca^{2+} saturated bentonite was allowed to dry at 60°C in a forced-drought oven. Similarly, separate batches of Mg^{2+} and K^+ saturated bentonite were prepared using 1 M $MgCl_2$ and 1 M KCl. After drying the Ca^{2+}, Mg^{2+}, and K^+ saturated clays were ground separately for mixing with soil.

Preparation of bentonite remediated soils

A series of 2 pot trials was established on soils collected from the surface horizons (0–20 cm) of the aforementioned degraded tea plantation and a degraded light-textured Ultisol. Soils (500-g lots) from each of the sites were placed in 25 polyethylene-lined pots. To give a set ratio of 8 : 4 : 1 of Ca : Mg : K saturated bentonite, the respective saturated clays were weighed to give an equivalent total application rate of 0, 10, 20, and 40 t/ha and thoroughly mixed with the soils. After mixing, a 20-g subsample was collected from each pot and analysed for pH, exchangeable cations, and exchangeable acidity. The experimental design was a completely randomised block design with 5 replicates.

Twenty forage sorghum seeds were sown in each of the pots and the water content was maintained at field moisture capacity (14.4% for Ultisol and 41.8% for Oxisol) by daily weighing. After 14 days, seedlings were thinned to 3 per pot. A basal fertilisation of nitrogen (N) and phosphorus (P) was applied to all treatments by applying a 5-mL solution each of N (55.9 mg N/kg soil as NH_4NO_3) and P (13.3 mg P/kg soil as $Na_2HPO_4.\ 2H_2O$). Above-ground biomass from each pot was harvested at 4-week intervals and 3 harvests were undertaken.

Statistical analyses

The analysis of variance (ANOVA) routine of GENSTAT (GENSTAT 5 Committee 1993) was used and the standard error of the means and least significant differences were calculated. Curves associated with the charge fingerprints were fitted using the curve fitting function of SigmaPlot 5.0 for Windows.

Results and discussion

Changes in soil chemical properties associated with changed land management

Mean soil pH, organic carbon, exchangeable basic and acidic cations, and ECEC to 70 cm for the undisturbed (forest) and disturbed (tea) sites are presented in Table 1. Soil pH under the disturbed site decreased by approximately 0.3–0.6 unit irrespective of depth, from that of the undisturbed forest. The decline in soil pH associated with changed land management may in part be attributed to the acidifying effects of nitrogenous fertilisers used in the growing of crops and the increased mineralisation of soil organic matter associated with land clearing (Rowell and Wild 1985; Aweto *et al.* 1992). Exchangeable Ca^{2+} and Mg^{2+} declined dramatically over all depth intervals on the disturbed site (Table 1). In contrast, there was a slight increase in K^+ in the surface horizon of the disturbed site, due to routine applications of K^+-based fertilisers to tea, but thereafter K^+ declined when compared with the undisturbed site. Over the past 53 years since conversion from climax forest to agricultural production, soil organic carbon declined significantly over all depth intervals. The loss of soil organic carbon from the tea site amounted to an equivalent of 58.1 t/ha over the 0–20 cm depth. This dramatic decline in soil organic carbon would have a significant impact on the soil's ability to retain cations and hence the inherent fertility of the disturbed site.

Charge properties and depreciation index

Charge fingerprints of composite soils collected from depth intervals 0–10, 20–30, and 50–70 cm for the rain forest and adjacent tea plantation are presented in Fig. 1. The amount

Table 1. Mean (standard error of the mean in parentheses) for pH, exchangeable cations, exchangeable acidity, effective cation exchange capacity (ECEC), and organic carbon (OC) for each depth interval for soil collected from the forested and tea sites in north Queensland

Characteristic	Site	Depth (cm)				
		0–10	10–20	20–30	30–50	50–70
pH_w	Forest	5.26(0.05)	5.26(0.04)	5.25(0.04)	5.24(0.06)	5.24(0.06)
	Tea	4.98(0.04)	4.63(0.06)	4.61(0.04)	4.67(0.06)	4.75(0.07)
Ca^{2+} ($cmol_c$/kg)	Forest	1.35(0.38)	0.49(0.16)	0.22(0.05)	0.09(0.02)	0.05(0.01)
	Tea	0.24(0.03)	0.05(0.01)	0.04(0.01)	0.03(0.01)	0.02(0.01)
Mg^{2+} ($cmol_c$/kg)	Forest	1.02(0.15)	0.48(0.10)	0.22(0.05)	0.09(0.03)	0.04(0.01)
	Tea	0.17(0.02)	0.06(0.01)	0.04(0.003)	0.02(0.003)	0.01(0.003)
K^+ ($cmol_c$/kg)	Forest	0.23(0.02)	0.16(0.01)	0.08(0.01)	0.03(0.01)	0.01(0.002)
	Tea	0.26(0.06)	0.06(0.01)	0.04(0.01)	0.03(0.02)	0.03(0.01)
Na^+ ($cmol_c$/kg)	Forest	0.09(0.002)	0.06(0.007)	0.04(0.003)	0.02(0.002)	0.01(0.001)
	Tea	0.04(0.005)	0.05(0.006)	0.03(0.004)	0.03(0.004)	0.03(0.003)
$Al^{3+} + H^+$ ($cmol_c$/kg)	Forest	0.25(0.01)	0.14(0.03)	0.10(0.03)	0.08(0.02)	0.04(0.02)
	Tea	0.15(0.02)	0.14(0.02)	0.01(0.006)	0.01(0.005)	0.02(0.01)
ECEC ($cmol_c$/kg)	Forest	2.94(0.54)	1.32(0.29)	0.69(0.13)	0.32(0.06)	0.16(0.03)
	Tea	0.85(0.10)	0.36(0.02)	0.17(0.01)	0.12(0.02)	0.11(0.02)
OC (mg/g)	Forest	66.2(2.6)	48.8(3.9)	33.8(3.8)	21.0(0.9)	15.6(0.9)
	Tea	35.4(1.0)	31.2(1.3)	23.8(1.2)	15.6(0.5)	12.2(0.7)

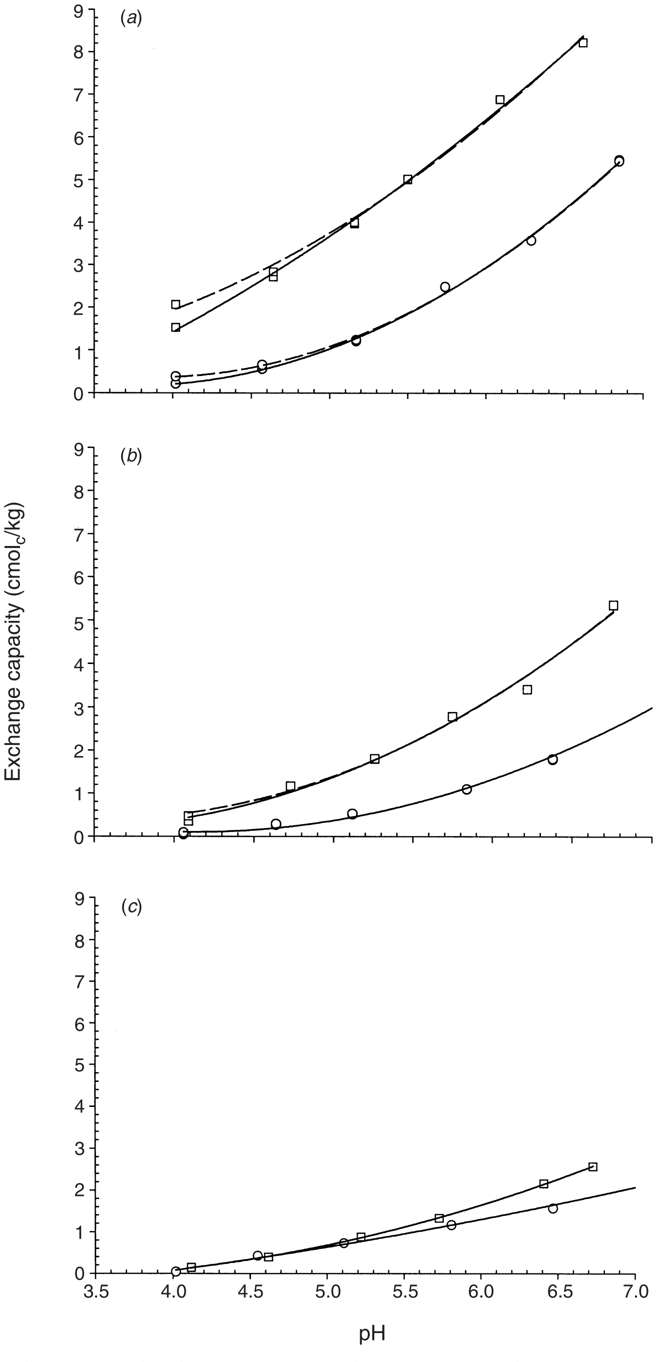

Fig. 1. Charge fingerprints for the (*a*) 0–10 cm, (*b*) 20–30 cm, and (*c*) 50–70 cm depths of soils collected from a tea plantation (○) and adjacent climax tropical rain forest (□) in north Queensland. CEC_T is represented by the dotted lines and CEC_B by the solid lines.

of negative charge generated over the pH range in the surface horizon ranged from 2.0 to 8.4 $cmol_c$/kg and 0.4 to 5.4 $cmol_c$/kg for the forest and tea sites, respectively. The degree of divergence between the 2 sets of curves decreased with depth so that at 50–70 cm there was little difference between curves (Fig. 1*c*). The degree of divergence between the curves may in part be a function of the changes in organic carbon content of the soil. In all cases the organic carbon content was higher under the forest site over all depth intervals (Table 1).

Chemical degradation of soil is a direct consequence of acidification that results in a decrease in exchangeable basic cations. In most variable-charged soils, an optimum soil pH for plant growth of 5.5 has been suggested, since at this pH phytotoxic levels of exchangeable Al^{3+} are eliminated and in most cases the additional cost associated with liming such soils above this pH value is unwarranted (Menzies and Gillman 1997). It is evident from the curves presented in Fig. 1 that there is a distinct convergence at pH 5.5 of the curves associated with CEC_B and CEC_T. Consequently, by evaluating the magnitude of the CECs of the 2 systems at pH 5.5 the degree of diminution in basic cation content can be assessed. The estimated CECs at pH 5.5 for the surface horizon were 4.94 and 1.86 $cmol_c$/kg for the forest and tea sites, but this decreased to 1.11 and 0.93 $cmol_c$/kg respectively at 50–70 cm depth (Table 2). This clearly demonstrates that the greatest changes in charge characteristics were evident in the surface horizon. In order to assess the degree of degradation that an individual system has undergone, Menzies and Gillman (1997) formulated a 'degradation index' (DI), expressed as:

$$DI = 100 \times (CEC_{5.5} - \Sigma \text{ basic cations}) / CEC_{5.5} \qquad (1)$$

where $CEC_{5.5}$ is the cation exchange capacity estimated from the charge fingerprint at pH 5.5; Σ basic cations is the sum of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ at soil pH. The DI for the surface horizon of the forest and tea plantation was calculated to be 45% and 61%, respectively, suggesting that the forest site had undergone a degree of degradation from the ideal associated with pH 5.5 (Table 2). In the current study it can be assumed that the undisturbed forest site represents what could be termed a 'benchmark' on which to assess degradation associated with changed land use. In this respect Noble *et al.* (2000) suggested that a more appropriate means of assessing degradation may best be described by a saturation index (S_u) as follows:

$$S_u = 100 \times (CEC_{u5.5} - \Sigma \text{ basic cations}_d) / CEC_{u5.5} \qquad (2)$$

Table 2. Selected charge characteristics and indices of composite samples from the 0–10 cm depth interval for the undisturbed forest and tea plantation sites

Depth (cm)		CEC_T[A]	ECEC	$CEC_{5.5}$ ($cmol_c$/kg)	Σ Cations	DI[C]	S_u[D] (%)
0–10	Forest	3.25	2.94	4.94	2.69	45	45
	Tea	0.67	0.85	1.85	0.72	61	85
20–30	Forest	0.93	0.69	2.16	0.56	74	n.a.
	Tea	0.16	0.17	0.77	0.15	81	n.a.
50–70	Forest	0.5	0.16	1.11	0.11	90	n.a.
	Tea	0.39	0.11	0.93	0.09	90	n.a.

n.a., not available.

[A] At soil pH. [B] K^+, Na^+, Mg^{2+}, Ca^{2+}. [C] Degradation index. [D] Saturation index.

where $CEC_{u5.5}$ refers to the cation exchange capacity on the *undisturbed* (forested) soil; Σ basic $cations_d$ is the sum of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Na^+ at soil pH for the *disturbed* (tea) soil. Consequently, the degree of degradation associated with changed land use as estimated by S_u increased to 85% for the surface horizon (Table 2). Clearly the conversion from climax rain forest to agronomic production has had a significant impact on the charge characteristics of the surface horizon. This decline in surface charge is directly related to a decline in soil organic matter.

It was interesting to note the differences in CEC_T and ECEC in the 0–10 and 50–70 cm depth intervals at soil pH for both the disturbed and undisturbed sites (Table 2). From a theoretical perspective these values should be similar, as was observed in the 20–30 cm depth interval (Table 2). Similar discrepancies were observed in surface soils by Noble *et al.* (2000) and were associated with an accumulation of soluble cations that were not associated with the exchange complex and therefore resulted in an overestimation of the ECEC. Since these soils were sampled in the dry season it is conceivable that an accumulation of cations associated with the mineralisation of organic matter may have occurred, and would therefore be subject to leaching at the onset of the wet season. This would effectively result in an overestimation of the ECEC. In contrast, at the 50–70 cm depth interval the CEC_T is larger than the ECEC (Table 2). This can be attributed to the generation of variable charge associated with an increase in the ionic strength of the equilibration solution used in the laboratory (i.e. 0.002 M $CaCl_2$) over and above that of the soil solution under natural conditions. This would result in an overestimation of CEC_T.

Remediation of charge characteristics

A plot of CEC_B immediately after the incorporation of bentonite versus the sum of basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) is presented in Fig. 2. The closeness of the values to the

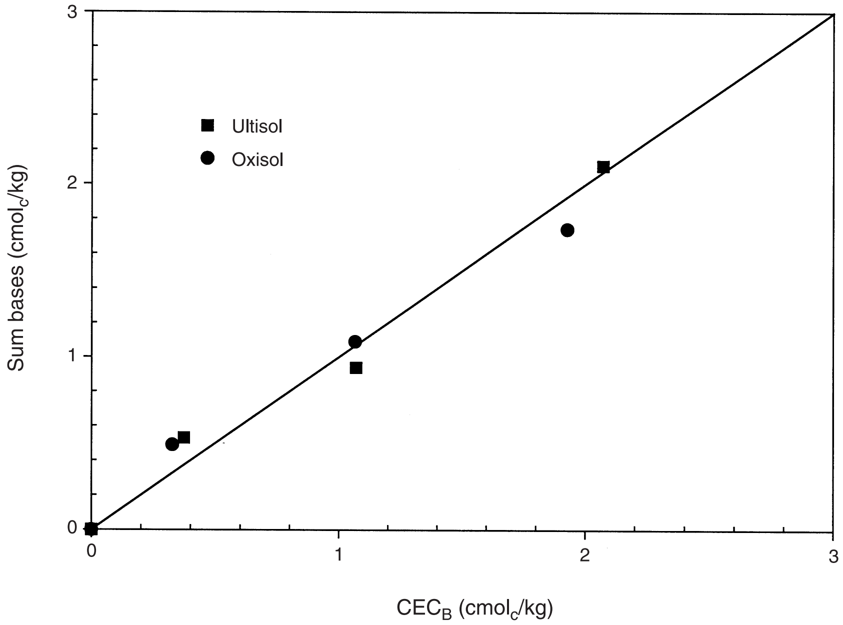

Fig. 2. Relationship between the change in CEC_B and the sum of basic cations after the addition of varying rates of beneficiated bentonite.

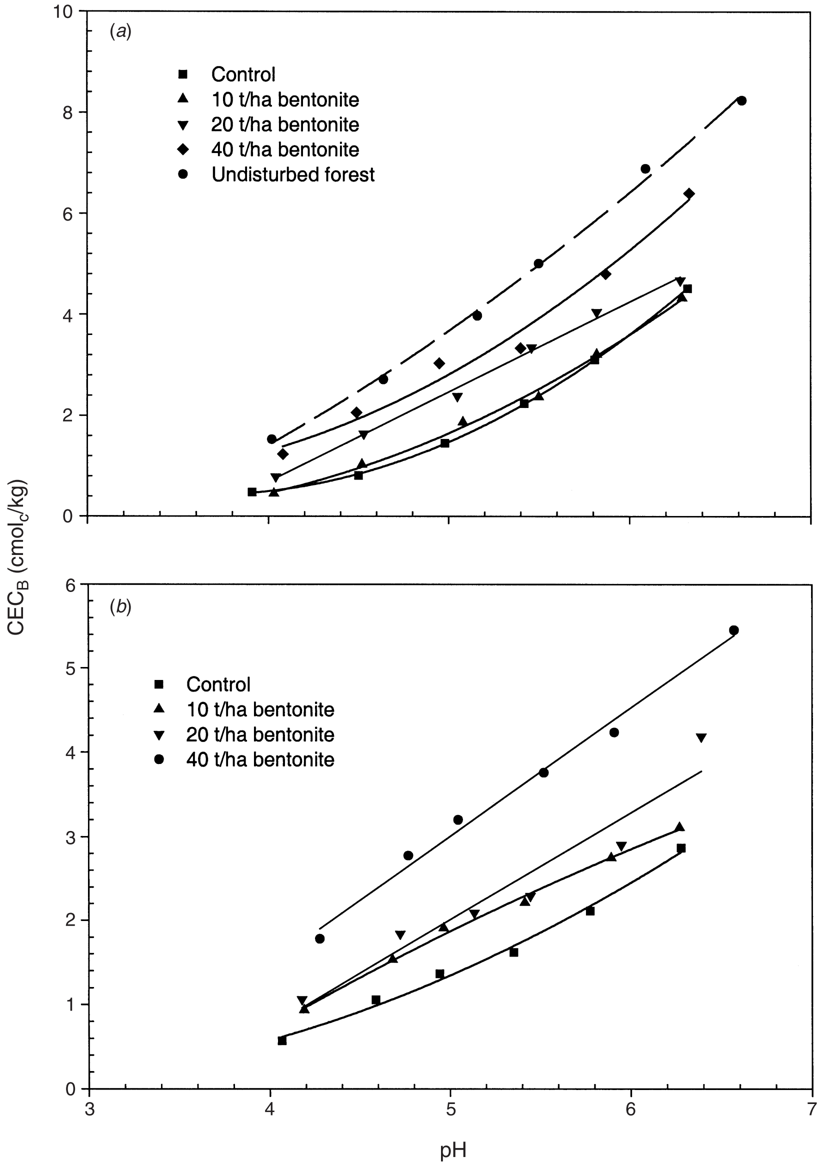

Fig. 3. Charge fingerprints for surface soils collected from (*a*) degraded tea plantation (Oxisol), and (*b*) sugarcane (Ultisol) field, after beneficiated bentonite applications.

1 : 1 line is indicative of the cations added to the bentonite being present in an exchangeable form. In addition, the relationship indicates the extent of cation benefication that has occurred with the addition of bentonite. In this respect the sum of exchangeable basic cations increased from 0.69 to 2.80 and 0.71 to 2.45 cmol$_c$/kg for the Utisol and Oxisol soils, respectively.

For brevity the agronomically significant CEC$_B$ curves for each of the sets of soils determined at the end of the study are presented in Fig. 3. Increasing additions of bentonite resulted in a vertical shift of the charge curves, with the greatest increase being at an equivalent rate of 40 t/ha. The extent of remediation can be best assessed by comparing the charge curves in the case of the Oxisol with that of the undisturbed pristine climax forest. It is clearly evident from Fig. 3*a* that there has been a substantial vertical shift in the $\mathrm{CEC_B}$ curve of the degraded tea soil towards that of the undisturbed forest. The extent of the vertical shift in the charge curves represents an increase in the **permanent** charge characteristics of the soils. In order to predict the degree of permanent charge generation associated with the addition of bentonite, the CEC at pH 5.5 was regressed against the rate of bentonite applied. The linear regression curve was forced through the origin and resulted in a significant linear correlation:

$$\mathrm{CEC\ (cmol_c/kg)} = 0.0428 \times \mathrm{rate\ (t/ha)} \qquad (r = 0.972)$$

Based on the aforementioned relationship, an application of 40 t/ha of bentonite would result in an increase in CEC of 1.71 $\mathrm{cmol_c}$/kg. This compares favourably with the predicted value of 2.05 $\mathrm{cmol_c}$/kg.

Plant response to cation remediation

Significant yield increases associated with the application of beneficiated bentonite were observed on each of the contrasting soil types, with the greatest increase in yield being observed at the highest rate of application (Table 3). It is of note that in the case of the Ultisol, there was a 10.3-fold increase between the control and the 40 t/ha application at the first harvest. This, however, had decreased to a 5.1-fold increase by the third harvest. In contrast, on the tea site there was a 1.9-fold increase over the aforementioned treatments at the first harvest but this increased to a 3.2-fold increase by the third harvest. The cumulative increase in yield between the control and 40 t/ha bentonite application was 7.7- and 3.1-fold increase for the Utisol and Oxisol production systems, respectively. Clearly the observed yield responses are associated with cation augmentation due to the addition of beneficiated bentonite (Table 4), since all treatments received basal applications of nitrogen and phosphorus. With increasing applications of beneficiated bentonite there was a corresponding increase in the amount of exchangeable basic cations (Table 4). Whilst it may be argued that similar responses could be achieved through the application of soluble

Table 3. Biomass production of forage sorghum (g/pot, dry weight) grown on soils on two contrasting soil types after the addition of beneficiated bentonite

Rate (t/ha)	Harvest 1	Harvest 2	Harvest 3	Cumulative yield
		Oxisol		
0	0.169	0.101	0.304	0.573
10	0.228	0.412	0.687	1.327
20	0.288	0.662	0.759	1.709
40	0.322	0.455	0.977	1.754
l.s.d. ($P = 0.05$)	0.114	0.149	0.115	0.213
		Ultisol		
0	0.123	0.068	0.115	0.306
10	0.214	0.177	0.297	0.687
20	0.439	0.412	0.538	1.388
40	1.277	0.482	0.596	2.355
l.s.d. ($P = 0.05$)	0.146	0.108	0.214	0.356

Table 4. Changes in cation ($cmol_c/kg$) contents associated with the addition of beneficiated bentonite clays to two contrasting soil types

Rate (t/ha)	Ca^{2+}	Mg^{2+}	K^+	Na^+
		Oxisol		
0	0.27	0.18	0.22	0.04
10	0.56	0.35	0.24	0.05
20	0.92	0.54	0.28	0.06
40	1.27	0.77	0.34	0.07
		Ultisol		
0	0.42	0.14	0.12	0.02
10	0.73	0.30	0.16	0.03
20	0.95	0.45	0.19	0.05
40	1.64	0.81	0.29	0.07

inorganic sources of Ca^{2+}, Mg^{2+}, and K^+, the long-term impact on the surface charge characteristics as demonstrated in this study would not occur through such a strategy.

Conclusions

The results from this study highlight the degree of surface charge degradation associated with anthropogenic disturbance that a soil in the humid wet tropics has undergone since conversion from its climax forest state to various forms of agronomic production. This decrease in charge properties is a function of the decline in soil organic matter invariably associated with the mixing of the soil through tillage operations. Consequently, the loss of CEC with an associated increase in acidity has resulted in the loss of basic cations from the exchange complex. The restoration of soil organic matter would reverse, in part, the aforementioned decline in CEC and cation loss associated with land conversion. However, this is not easily attainable in tropical and subtropical regions where regular cultivation is undertaken. In addition, if adequate levels of soil organic matter were available to facilitate such an undertaking, the increase in CEC and fertility would be transitory, since the whole cycle of degradation would be repeated on soil disturbance.

This study has clearly shown that the application of relatively low rates of beneficiated bentonite has the ability to significantly increase the surface charge characteristics and enhance productivity on two contrasting degraded soil types commonly found throughout the tropics. The addition of highly charged bentonite clays has resulted in a dramatic increase in **permanent** negative charge of these degraded soils, which is in contrast to the predominantly **variable** charge nature of organic matter.

Acknowledgments

The authors acknowledge the financial contribution of the FAO/World Bank Project entitled ‘Forestry Research Education and Extension Project’ in supporting the co-authors on a training visit to Australia. In addition, the authors thank Ms S. Berthelsen for her technical support in the analysis of samples.

Declaration

The technology discussed in this paper is the subject of an International Patent Application No. PCT\AU01\00026.

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Manuscript received 3 August 2000, accepted 14 March 2001