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Contribution to the knowledge of a solonetzic, magnesium-rich alluvial silty clay in the Maro-Koembe plain

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Summary

Soil survey of a part of the Maro-Koembe grass plain in West Irian (Indonesia) and analysis of several profiles reveal that the alluvial sediment is in an initial stage of soil formation. The chemical analysis, however, clearly indicates that the soil formation processes will lead to the formation of an alfisol, more specifically, to a natraqualf. Investigation of the cation-exchange characteristics and the soil solution shows that the Ca-ion seems to be removed more intensively from the surface layer than the Mg-ion. This is an apparent effect, as it appeared that Mg is strongly released by the minerals upon weathering. Before being released to the solution these ions pass the adsorbed state, giving rise to a high Mg-saturation of the exchange complex.

The distribution coefficient for the Ca/Mg exchange equilibrium is supposed to be 1.2. The higher coefficient (1.4) in the A-horizons of the most strongly leached soils is believed to be due to the organic matter in these horizons. The lower coefficient (1.0) in the deeper horizons is due to the above mentioned mechanism of Mg-release.

The distribution coefficients for the Ca/Na and Mg/Na exchange equilibria are 1,8, if defined in terms of the Gapon equation of ion-exchange and 1.3, if defined in terms of the Vanselow- or Heald, Frere and de Wit-equation of ion-exchange.

On the basis of these findings, it seems possible to predict the change in cation-exchange characteristics of the investigated soils upon further leaching and to predict the soil group, to which the soils will develop.

Introduction

In view of the intention of the Dutch Government to plan a rice growing project in the area between the Maro- and Koembe river in the former South New Guinea, this area was mapped by means of a semi-detailed soil survey, undertaken by Reynders and Andriesse with the help of aerial photographs (Reynders, 1961).

The Nedeco (Nederlands Adviesbureau voor Ingenieurswerken in het Buitenland) enabled the senior author to carry out a more detailed and supplementary survey to gain a deeper insight into the different aspects of this project.

This paper deals with the changes taking place in the alluvial deposit upon proceeding soil formation and leaching.

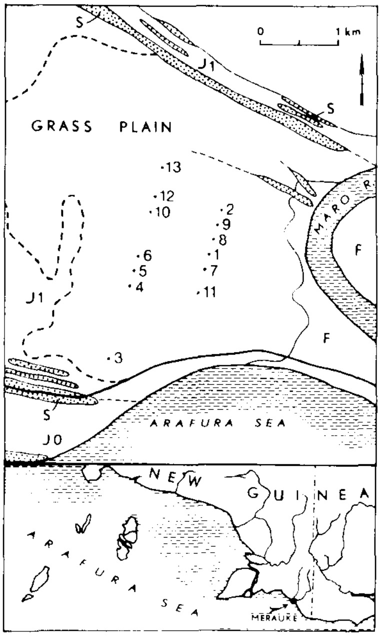

Fig. 1 Soil map and situation sketch of the area studied. S: sandridges, J0 + J1: young landscape, F: fluviatile soils, 1–13 : soil pits and — : track.

General description of the area

Geography

The area studied is situated in the southern coastal plain of West Irian (Indonesia) just west of the city of Merauke (see situation sketch in Fig. 1).

The boundaries are formed in the east and west by the rivers Maro and Koembe, in the North by the Ridge of Wentholt (a system of clay-, sand- and shell-ridges) and in the south by a system of young beach ridges.

The Maro-Koembe plain has a sparse population and is hardly accessible.

Geology

The area is the youngest part of the great coastal plain, known as the Digul Fly depression, as described by Reynders (1961). In the past there has been a number of marine transgressions and regressions. Former coastal lines are marked by sand ridges. Some of these ridges have been covered by sediments resulting in a weakly wavy topography.

Climate

The climate is typically monsoonal. One rainy period can be noticed. The annual precipitation has an average of 1630 mm with the following monthly distribution (in mm):

Jan.	Febr.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
265	235	256	184	137	43	36	21	31	46	81	195

The rainfall in the rainy season is too high to be discharged completely; therefore, the plain is transformed periodically into a swamp.

Topography

The topography of the plain is flat, however, with a weakly wavy character. The elevation is 5–6 m above the mean low-water level. The ridges in the south and north are considerably higher. The high-water level is about 5.5 m above the low-water level.

Vegetation

There are three vegetation types: a) brackish-water vegetation, b) secondary forest vegetation, and c) grass vegetation.

The brackish-water vegetation is found along the borders of both rivers. The zone along the Maro river is rather narrow, whereas the zone along the Koembe river is wide, due to many old river channels. It consists mainly of mangroves.

The secondary forest grows on the beddings of deserted gardens of the natives. The trenches do not carry a vegetation. *Naudea orientalis* dominate in the more open spaces, Palmae and several trees of the *Barringtonia* formation are found in the wooded areas and *Pluchea indica* occurs in thickets.

The grass vegetation forms a uniform grass plain. The lower parts have a cover of *Arundinella* and *Ischeanum* species, whereas the higher parts are covered with *Imperata cylindrica.* The Maro river is bordered with salt tolerant grasses and sedges.

Table 1 Physical and chemical data of the soil

Hor.	*Grain size distribution*			*pH sat. $CaSO_4$*	*$CaCO_3$ (%)*	*C (%)*	*C/N*	*Exchange cations meq./100 g of soil*				*c.e.c. meq./100 g*
	2–0.05 mm (%)	*0.05–0.002 mm (%)*	*< 0.002 mm (%)*					*Ca*	*Mg*	*Na*	*K*	
A_1	1.5	42.3	56.2	6.02	—	4.25	9.7	12.8	12.8	3.7	0.2	30.3
B_{21}	0.8	31.1	68.1	7.22	—	1.12	7.1	14.9	13.6	2.8	0.2	33.1
B_{22g}	0.4	37.9	61.7	7.25	15.6	0.50	6.7	13.4	10.3	2.4	0.3	25.7
C_{1g}	0.6	41.4	58.0	7.28	18.1	0.36	5.8	11.4	9.3	3.2	1.0	24.5
C_{2g}	1.4	47.5	51.1	7.31	22.3	0.34	6.2	10.0	9.1	2.4	0.6	21.5

Table 2 Partial elemental analysis of the soil

Hor.	*SiO_2 (%)*	*Al_2O_3 (%)*	*Fe_2O_3 (%)*	*CaO (%)*	*MgO (%)*	*MnO (%)*	*TiO_2 (%)*	*'free iron' (%)*	*SiO_2/Al_2O_3*	*SiO_2/Fe_2O_3*	*Al_2O_3/Fe_2O_3*
A_1	59.4	16.8	4.37	1.00	1.22	0.03	0.30	1.13	6.02	36.3	6.03
B_{21}	56.7	19.9	8.73	0.78	1.70	0.04	0.32	4.03	4.85	17.3	3.56
B_{22g}	48.7	15.8	6.24	9.46	1.93	0.14	0.28	2.12	5.24	20.8	3.97
C_{1g}	48.8	14.9	5.72	10.8	1.97	0.13	0.28	1.92	5.59	22.7	4.07
C_{2g}	48.7	13.7	5.31	11.5	1.93	0.10	0.27	1.82	6.05	24.4	4.04

Description and analysis of the standard soil profile

As all profiles differ only slightly in thickness of horizons, one representative profile will be described:

4–0 cm	O_1	Felty sod layer
0–3 cm	A_1	Dark grey (10 YR 4/1 : d) to black (10 YR 2/1 : m) silty clay. Compact, porous and firm. Many roots. Non-calcareous. Clear and smooth boundary to:
3–13 cm	B_{21}	Grey brown (2.5 Y 5/2 : d) to dark grey brown (2.5 Y 4/2 : m) clay. Compound, moderate, very coarse prismatic and moderate coarse angular blocky structure. Firm. Sticky and plastic when wet. Few, distinct, brownish-yellow (10 YR 6/8) mottles. Humus- (and clay-?) coatings on the structural elements. Some roots. Non-calcareous. Gradual and smooth boundary to:
13–31 cm	B_{22g}	Light grey (5 Y 7/2 : d) to olive grey (5 Y 4/2 : m) clay. Compound, moderate, very coarse prismatic and moderate, coarse angular blocky structure. Firm. Plastic and sticky when wet. Many, distinct, yellowish brown (10 YR 5/8) mottles. Humus- (and clay-?) coatings on peds. Very few roots. Calcareous. Gradual and smooth boundary to:
31–56 cm	C_{1g}	Light grey (5 Y 7/1 : d) to olive grey (5 Y 5/2 : m) silty clay. Massive and firm. Plastic and sticky when wet. Many Mn-concretions. Humus infiltration. No roots. Strongly calcareous. Clear and smooth boundary to:
> 56 cm	C_{2g}	Light grey (5 Y 7/2 : d) to light olive grey (5 Y 6/2 : m) silty clay. Massive and firm. Plastic and sticky when wet. Many Mn-concretions and common, diffuse, brownish yellow (10 YR 6/8) mottles. Strongly calcareous.

The analyses are shown in Table 1 and 2.

Table 1 shows that, although the upper 13 cm of the profile has already been decalcified, base saturation has not changed. There is some clay movement, indicating that upon further leaching, textural B-horizons will be formed. Table 2 demonstrates than iron is appreciably displaced from the A_1 to the B_{21} horizon, as well as aluminium. The translocation, however, is over a short distance. Manganese is displaced from the A_1 and B_{21} horizon and accumulated in the B_{22g} and C_{1g} . The conclusion is that the soil is in an initial stage of soil formation, but will develop into an alfisol and probably specifically into a natraqualf. In its present stage it has to be classified as a haplaquent. As the analysis shows that the soil formation process tends to the formation of a textural B-horizon and because the profile is natric, the soil could be best classified as natraqualfic haplaquent. According to the 1964 Supplement to the 7th Approximation these soils would be probably classified as 'typic normaquepts'.

Cation-exchange characteristics and composition of 2 : 1 water extracts

Although soil formation is not yet pronounced, it is presumable that the cation-exchange characteristics of the soils differ in dependence of the position above the groundwater table. Therefore the soils were grouped into three moisture classes (Fig. 1), viz. I, soils with an average lowest groundwater table of 132 cm (prof. 11, 12 and 13); II, soils with a mean lowest groundwater level of 114 cm (prof. 7, 8, 9 and 10) and finally III, soils with a mean lowest groundwater table of 98 cm (prof. 1, 2, 3, 4, 5 and 6). Of these profiles the cation-exchange and 2 : 1 extract characteristics were determined, using the method of Yaalon et al. (1962). It was not possible to determine the composition of saturation extracts, as the volume extracted was too small to allow the estimation of the ions even on a microchemical scale. (The clay fraction contained predominantly montmorillonite and swelling illite.) The data of the three groups are compared with those of the parent material, the upper boundary of which is situated at an average of 58 cm above the lowest groundwater level.

The results of the A-horizons of the three groups are given in Table 3 and 4. As expected, the ionic strength of the water extract is lowest for the A-horizons of the soils with the lowest groundwater table. The reduced ratios $\sqrt{Ca}/Na$ and $\sqrt{Mg}/Na$ show that Na is stronger leached than the divalent ions, which is very well known

Table 3 Water extract composition of the A-horizon and of the C-horizon

	Ion-conc. in moles × 10³ per litre							Ca/Mg	$\sqrt{Ca/Na}$	$\sqrt{Mg/Na}$	μ moles × 10³ per litre
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}				
IA	1.0	1.7	10.0	—	3.0	7.7	2.0	0.59	3.2	4.1	19.7
IIA	2.0	2.5	14.0	—	3.5	11.5	3.5	0.80	3.2	3.6	30.5
IIIA	2.5	2.8	21.5	0.2	4.2	18.1	5.0	0.90	2.3	2.4	42.6
C_g	5.0	3.8	32.0	0.5	2.5	22.0	13.5	1.33	2.2	1.9	73.1

Table 4 Cation exchange characteristics of the A- and C-horizons

	Exchangeable cations in meq./100 g of soil				Ca/Mg	$\sqrt{Ca/Na}$	$\sqrt{Mg/Na}$	c.e.c. in meq./100 g
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}				
IA	12.0	14.8	1.5	0.2	0.81	2.31	2.57	30.0
IIA	14.0	15.8	2.6	0.1	0.89	1.44	1.53	34.6
IIIA	12.5	13.4	3.0	0.3	0.93	1.18	1.22	32.0
C_g	10.8	8.1	2.8	0.4	1.33	1.18	1.02	25.4

too. However, the trend in the Ca/Mg ratio indicate that Ca seems to be stronger leached, than Mg, which is not to be expected. This has its bearing on the cation-exchange characteristics of the soils (Table 4).

Table 4 shows that the soils with the lowest groundwater level have the highest contents of exchangeable Mg. Furthermore it appears that the Ca/Mg ratio decreases with the lowering of the groundwater table, indicating that the exchange complex is relatively enriched with Mg. In other words, the exchange complex becomes increasingly saturated with Mg upon continuing leaching. However, it seems that after a certain stage the amount of exchangeable Mg decreases (compare IA and IIA in Table 4) and it could be expected that finally also the Ca/Mg ratio would increase upon further leaching.

The reduced ratios $\sqrt{Ca}/Na$ and $\sqrt{Mg}/Na$ give the expected trends. The monovalent cations are stronger leached than the divalent cations.

The same tendencies as described above for the A-horizons are also demonstrated by the B-horizons of the soils. The data are given in Table 5 and 6.

So far, the most interesting result is the peculiar behaviour of Mg^{2+} and Ca^{2+} upon leaching. The equilibrium: adsorbed ions $\rightleftarrows$ dissolved ions, is described by the equation[1]:

$$\frac{(Ca^{2+})_a}{(Mg^{2+})_a} = \frac{(Ca^{2+})_d}{(Mg^{2+})_d} \tag{1}$$

Table 5 Water extract composition of the B- and C-horizons

	Ion-conc. in moles × 10³ per litre							Ca/Mg	$\sqrt{Ca/Na}$	$\sqrt{Mg/Na}$	μ moles × 10³ per litre
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}				
IB	1.4	1.75	11.1	—	2.0	7.9	3.75	0.80	3.4	3.8	24.3
IIB	2.6	2.45	18.0	0.15	2.55	12.3	6.9	1.04	2.8	2.7	40.4
IIIB	2.8	2.4	23.5	0.15	2.1	18.0	7.1	1.17	2.2	2.1	46.5
C_g	5.0	3.8	32.0	0.5	2.5	22.0	13.5	1.33	2.2	1.9	73.1

Table 6 Cation-exchange characteristics of the B- and C-horizons

	Exchangeable cations in meq./100 g of soil				Ca/Mg	$\sqrt{Ca/Na}$	$\sqrt{Mg/Na}$	c.e.c. in meq./100 g
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}				
IB	11.2	11.8	2.1	0.3	0.95	1.60	1.64	27.2
IIB	12.2	12.2	2.2	0.3	1.00	1.60	1.60	29.4
IIIB	11.6	10.6	2.9	0.4	1.10	1.17	1.12	28.6
C_g	10.8	8.1	2.8	0.4	1.33	1.18	1.02	25.4

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[1] For theories on ion adsorption, see i.a. Vanselow (1932), Bolt (1955), Heald et al. (1964).

where brackets denote activities and subscripts a and d denote adsorbed and dissolved, respectively. The activities of the ions in the equilibrium solution are expressed in moles/l and those of the exchangeable cations e.g. as equivalent- or mol. fraction (equivalents or moles per unit amount of exchange capacity). Equation 1 can be written as follows:

$$\frac{(f_{Ca})_a Ca_a^{2+}}{(f_{Mg})_a Mg_a^{2+}} = \frac{(f_{Ca})_d[Ca^{2+}]_d}{(f_{Mg})_d[Mg^{2+}]_d} \quad \text{or:}$$

or:

$$\frac{Ca_a^{2+}}{Mg_a^{2+}} = \frac{(f_{Mg})_a(f_{Ca})_d[Ca^{2+}]_d}{(f_{Ca})_a(f_{Mg})_d[Mg^{2+}]_d} \tag{2}$$

where Ca_a^{2+} and Mg_a^{2+} denote the equivalent fractions of Ca^{2+} and Mg^{2+} adsorbed, $(f_{Mg})_a$ and $(f_{Ca})_a$ the activity coefficients of adsorbed Ca^{2+} and Mg^{2+}, respectively, $(f_{Ca})_d$ and $(f_{Mg})_d$ those of dissolved Ca^{2+} and Mg^{2+}, respectively, and where square brackets indicate molar concentrations.

If the equilibrium solutions are not too concentrated $(f_{Ca})_d/(f_{Mg})_d$ is unity and equation 2 reduces to:

$$\frac{Ca_a^{2+}}{Mg_a^{2+}} = k_{Ca,Mg}\frac{[Ca^{2+}]_d}{[Mg^{2+}]_d} \tag{3}$$

where k is the distribution coefficient and equals $(f_{Mg})_a/(f_{Ca})_a$. This coefficient can be constant under certain conditions, depending on the ionic strength and composition of the solution, and on the type of clay mineral present. Table 7 shows some data obtained from Table 3–6, expressed according to equation 3 and arranged according to increasing ionic strength of the water extract (equilibrium solution).

Table 7 Distribution of Ca^{2+} and Mg^{2+} in the soils, expressed in terms of equation 3

	$\frac{Ca_a^{2+}}{Mg_a^{2+}}$	$k_{Ca,Mg}$	$\frac{[Ca^{2+}]_d}{[Mg^{2+}]_d}$	μ *moles × 10^3 per litre*
IA	0.81	1.4	0.59	19.7
IB	0.95	1.2	0.80	24.3
IIA	0.89	1.1	0.80	30.5
IIB	1.00	1.0	1.04	40.4
IIIA	0.93	1.0	0.90	42.6
IIIB	1.10	1.0	1.17	46.5
C_g	1.33	1.0	1.33	73.1

The table shows that in solutions with ionic strengths larger than about 0.040 M/l that seems to be no adsorption preference for either Ca or Mg. Furthermore it appears that the soils with a lower groundwater table contain much less dissolved Ca than dissolved Mg with the subsequent result that the Mg-saturation of the exchange complex is greater than the Ca-saturation, notwithstanding the fact that Ca^{2+} is preferentially adsorbed in the surface horizon. This peculiarity can only be explained by assuming that either Ca^{2+}-ions move more readily downward than Mg^{2+}-ions upon leaching or Mg^{2+}-ions are released from the clay minerals and/or primary minerals upon weathering (Nutting, 1945; Barshad, 1960). The authors believe the last assumption the most probable one. To gain support for this a certain amount of the soil parent material was shaken for 1 day with a weighed amount of the solution used for estimating exchangeable cations (being a mixture of LiOAc and LiCl buffered at pH 8.2). After this shaking time the system was centrifuged, the supernatant decanted and the residue weighed. This procedure was repeated six more times. By estimating Mg in the decanted solutions, the release of Mg could be studied. The results are given in Fig. 2 as a cumulative curve. It shows that after the fifth 'equilibration' a kind of 'steady state' release of Mg is arrived at. Anyway, it shows that the soil material, probably the clay minerals of it, are not at all stable, even not at pH 8. [2]

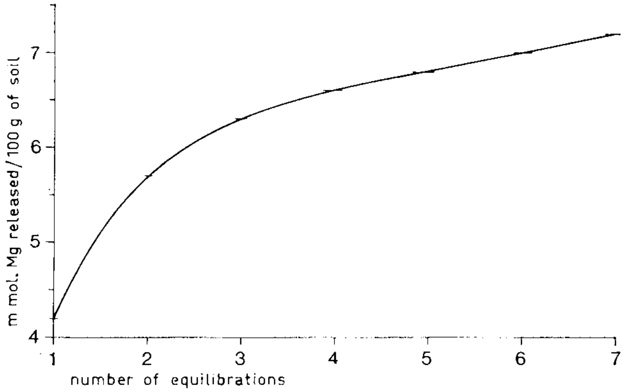

Fig. 2 Cumulative curve of released Mg after successive equilibrations with extraction solution.

This phenomenon could be the reason of the above stated cation-exchange characteristics of soils with different states of leaching. It is also an explanation for the fact that the Mg saturation of the exchange complex of the surface horizons is greater than Ca-saturation, as Mg, before being released into the soil solution, passes the adsorbed state. The authors are of the opinion that this mechanism is one of the possible modes in the formation of natric horizons.

The fact that Mg saturation has decreased in the A-horizon of the strongest leached soils (group I) is possibly caused by the fact that Mg release here is in the 'steady state', so that Ca-ions can compete with Mg-ions, this competition being favoured by the higher organic matter content of the A-horizon of these group of soils. The authors are of the opinion that the value of $k_{Ca,Mg}$ of 1.2 will be the most probable values for the distribution of Ca and Mg if no other effects are interfering.

The relation for the exchange equilibrium of mono- and divalent cations can be

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[2] This means that in the estimation of exchangeable cations the equilibration time should be taken as short as possible.

expressed by (according to Bolt, 1955):

$$\frac{M^{2+}}{M^{+}} = k_{M^{2+},M^{+}} \frac{\sqrt{(M^{2+})_d}}{(M^{+})_d} \tag{4}$$

where M^{2+} and M^{+} are the amounts of adsorbed divalent and monovalent cations, respectively, in meq. per gram of soil, $(M^{2+})_d$ and $(M^{+})_d$ are the activities of the divalent and monovalent cations, respectively, in the equilibrium solution expressed in moles/l, and $k_{M^{2+}M,^{+}}$ is the distribution coefficient in $m^{\frac{1}{2}} l^{-\frac{1}{2}}$.

Recently Heald et al. (1964) developed a new concept with respect to ion exchange. Their considerations lead to the following equation:

$$\frac{\sqrt{M^{2+}}}{(M^{+}} = k^{1}_{M^{2+},M^{+}} \frac{\sqrt{(M^{2+})_d}}{(M^{+})_d} \tag{5}$$

which is, however, exactly equal to the equation, developed by Vanselow (1932; see Bolt, 1967).

In equation 5 M^{2+} and M^{+} are the absorbed amounts of di- and monovalent cation, respectively, in equivalents per unit amount of exchange capacity (equivalent fraction), $(M^{2+})_d$ and $(M^{+})_d$ are the activities of the di- and monovalent cations, respectively, in the equilibrium solution in equivalent per litre, and $k^{1}_{M^{2+},M^{+}}$ is the ratio of the square root of the normalized formation constant of the divalent cations and the formation constant of the monovalent cations with the cation exchanger (dimensions: eq. $^{\frac{1}{2}}l^{-\frac{1}{2}}$).

Table 8 The distribution coefficients for the Ca/Na- and Mg/Na-exchange

	$k_{Ca,Na}$ $m^{\frac{1}{2}} l^{-\frac{1}{2}}$	$k_{Mg,Na}$ $m^{\frac{1}{2}} l^{-\frac{1}{2}}$	$k^{1}_{Ca,Na}$ $eq^{\frac{1}{2}} l^{-\frac{1}{2}}$	$k^{1}_{Mg,Na}$ $eq^{\frac{1}{2}} l^{-\frac{1}{2}}$	μ *moles* × *103* *per litre*
IA	2.4	2.4	1.5	1.7	19.7
IB	1.6	1.5	1.1	1.0	24.3
IIA	1.7	1.7	1.2	1.4	30.5
IIB	2.0	2.0	1.4	1.4	40.4
IIIA	1.8	1.8	1.5	1.5	42.6
IIIB	1.7	1.8	1.3	1.2	46.5
C_g	1.8	1.5	1.2	1.1	73.1
Mean	1.8	1.7	1.3	1.3	

Table 8 contains the results of the calculations of the distribution coefficients according to e.g. equation 4 and 5 for the Ca/Na- and Mg/Na-exchange in the soils of this study. It appears that there is no definit trend in the distribution coefficients with respect to the composition of the soil solution and its ionic strength. The results for the IA horizon are rather deviating, probably because organic matter has some effect here. Therefore the values for this horizon are excluded in the calculation of the average.

Heald et al. (1964) determined the distribution coefficients for the Sr/Na- and Sr/Ca-exchange on Dowex-50 resin. From these values the coefficient for the Ca/Na-exchange can be computed. The result, 2.65 $\text{eq.}^{\frac{1}{2}}\,\text{l}^{-\frac{1}{2}}$, is much higher than our value of 1.3. This is in accordance with theory, as Dowex-50 resin has a much higher exchange capacity than the soils under investigation here.

Concluding it can be stated that it is now possible to predict the change in cation exchange characteristics of the soils of the Maro-Koembe plain upon further leaching.

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