EXTRACTABLE FORMS OF ALUMINUM AS AFFECTED BY GYPSUM AND LIME AMENDMENTS TO AN ACID SOIL

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ABSTRACT

The influence of gypsum or lime + gypsum amendments on various extractable forms of aluminum (Al) in a reconstructed acid soil (plinthic Palexerult) was investigated. The addition of gypsum depolymerized non-hydrolysable carbon (C) and increased the extraction of Al bound to organic matter. The application of gypsum or lime + gypsum lowered the levels of exchangeable Al; also, the low proportion of Al in outflow solutions suggests the immobilization of Al as a solid phase. Except for exchangeable Al, the gypsum amendment increases the proportion of all forms of Al extracted (bound to organic matter, sorbed to, oxalate and citrate) with various selected reagents relative to unamended samples. The amount of Al extracted increases with increase of

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gypsum added. The gypsum or lime + gypsum amendments increased soil productivity.

INTRODUCTION

Aluminum is the most abundant metallic element in soils. The effects of Al on the properties and behavior of soil arise from various phenomena that depend on the specific form of the element in soil. Thus, soluble or easily extracted Al forms have phytotoxic effects. Interlayered hydroxy Al compounds in clay minerals, amorphous hydrous oxides associated with clay surfaces and, possibly, Al organic complexes may play prominent roles in the retention of anions and cations, the lowering of the cation-exchange capacity, soil aggregate stability, and other physical properties such as infiltration rate and water retention.

The efficiency of gypsum and lime as ameliorants for soil acidity has been demonstrated by many authors (1,2); their addition leads to substantially increased yields in a wide variety of crops. This effect is usually due to an increased supply of Ca$^{2+}$ and a decreased level of exchangeable Al in the soil, both of which result in improved root proliferation in the subsoil and in increased availability of water. However, very little is known about the effect of gypsum and lime on other forms of Al also present in the soil. This interest prompted us to undertake the present work.

MATERIALS AND METHODS

The study was carried out on a plinthic Palexerult soil from the Cañameros “raña”, a geomorphological surface developed over continental sediments during the Middle to Upper Pliocene that was exposed to a climate with warm, wet summers prior to the Pleistocene. The soil is acid, has a low organic matter content, is very stony (especially on the surface), and also is highly weathered. It was useless for cropping purposes, mainly because of Al toxicity in addition to considerable calcium (Ca) and, possibly, magnesium (Mg) deficiencies. The most salient features of the soil profile are in Table 1.

A height of 1 m of the profile was reconstructed in PVC columns of 5 cm internal diameter, using the horizon thickness and bulk densities of the natural earth from the Ap, AB, and Bt1 horizons (1.6, 1.3, and 1.2 g cm$^{-3}$, respectively). Two columns were washed weekly with 200 mL of deionized water (unamended sample, C0). Volumes of 200 mL of a 2 g L$^{-1}$ gypsum solution were added on a weekly basis until a rate of 20 or 40 t ha$^{-1}$ was reached (columns C1, C3 and duplicates of both). Samples from the Ap horizon were supplied with lime at a rate of 17.5 t ha$^{-1}$ and incubated for 5 weeks with wetting to field capacity; this
new Ap horizon was used to prepare soil column C5 and its duplicate. To these last columns, 30 t of gypsum ha$^{-1}$ were also added. Following gypsum additions, each soil column was supplied with 200 mL of deionized water on a weekly basis. Leaching was terminated when the EC of the leachate was constant (0.2 dS m$^{-1}$).

The amount of supplied water was equivalent to 2.5 rainfall years (the average annual precipitation in the area is about 900 mm). The outflow solutions of the treatments and leachates were analyzed for sodium (Na), potassium (K), and Ca (flame photometry); Mg and Al (atomic absorption), silicon (Si) (ICP spectroscopy); and EC (conductimetry).

After the leaching treatments were completed, the soil columns were air-dried to a degree permitting collection of soil samples. The soil columns were exposed into halves by sawing the PVC cylinders vertically; from the exposed columns, the corresponding horizons (Ap, AB, and Bt1) were sampled. These samples were air-dried prior to analyzing the fractionation of Al as exchangeable, bound to organic matter, sorbed, and oxalate, citrate (3) and dithionite-citrate-bicarbonate (dcb) (4) extractable, determining exchangeable cations, and organic matter, and examining by X-ray diffraction.

Minerals were identified by using a Philips X’Pert diffractometer. Semi-quantitative estimates for the minerals were obtained from XRD random powder and oriented aggregate patterns, using the intensity factors reported by Schultz (5). For each horizon, the whole sample (≤2 mm) and the clay fraction (≤2 μm) extracted by sedimentation, were studied. Total carbon was determined by using a Strohlein CS-MAT 550 automatic analyzer and the fractional composition of humus by the modified method of Tiurin (6).

Productivity tests were carried out on pots where the soil profile corresponding to the Ap (200 g of the ≤2 mm fraction) and AB (100 g of the ≤2 mm fraction) horizons was reconstructed; the pots were subjected to the same

**Table 1. Main Morphological and Chemical Characteristics of the Soil Profile**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Depth cm</th>
<th>Color</th>
<th>pH</th>
<th>OM g kg$^{-1}$</th>
<th>Sand g kg$^{-1}$</th>
<th>Silt g kg$^{-1}$</th>
<th>Clay g kg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>0–33</td>
<td>10YR3/2.5</td>
<td>5.1</td>
<td>4.3</td>
<td>29.9</td>
<td>692</td>
<td>250</td>
</tr>
<tr>
<td>AB</td>
<td>33–56</td>
<td>10YR5/5</td>
<td>4.9</td>
<td>4.3</td>
<td>5.4</td>
<td>558</td>
<td>221</td>
</tr>
<tr>
<td>Bt1</td>
<td>56–100</td>
<td>7.5YR5.5/6</td>
<td>4.8</td>
<td>4.3</td>
<td>4.0</td>
<td>509</td>
<td>167</td>
</tr>
<tr>
<td>Bt2</td>
<td>100–210</td>
<td>2.5YR4/7</td>
<td>4.8</td>
<td>4.2</td>
<td>nd</td>
<td>483</td>
<td>104</td>
</tr>
</tbody>
</table>

nd: not determined.
treatments applied to the columns (viz. gypsum at 20 and 40 t ha\(^{-1}\) and incubation with 17.8 t lime ha\(^{-1}\) prior to addition of 30 t gypsum ha\(^{-1}\)). From each experiment four replicates were prepared using the appropriate amounts of (NH\(_4\))H\(_2\)PO\(_4\), NH\(_4\)NO\(_3\), KNO\(_3\) and urea as fertilizers. The productivity was evaluated in terms of seed nascence and leaf and root weight using *Raphanus sativus*.

**Figure 1.** Chemical analysis for Mg, K, Al, Na, Ca, and Si, in the outflow solutions of treatments and leachates. C1 samples treated with 20 t gypsum ha\(^{-1}\); C3 samples treated with 40 t gypsum ha\(^{-1}\); C5 samples treated with 17.5 t lime ha\(^{-1}\) +30 t gypsum ha\(^{-1}\).
RESULTS AND DISCUSSION

The chemical analysis of the leachates from the columns and those resulting from the washing process following gypsum (columns C1 and C3) and lime + gypsum (column C5) addition (Fig. 1) provided similar results. Sodium was the first leached element; its concentration in the leachate peaked at an amount of gypsum added of about 10 t ha\(^{-1}\). Silicon, Mg, and Ca leaching started at a gypsum rate about 15 t ha\(^{-1}\). The highest concentration of leached Mg (45 mg l\(^{-1}\)) was obtained with gypsum added at 20 t ha\(^{-1}\) rate. The addition of lime lowered the concentration of Mg in the leachate to 36 mg l\(^{-1}\). The lime + gypsum accelerated the Si concentration peak in the leachate (at 20 t gypsum ha\(^{-1}\)) relative to the addition of gypsum (28 t ha\(^{-1}\) alone; however, the highest leached concentration was the same in both cases (15 mg l\(^{-1}\)). The amount of leached Ca increased with the addition of gypsum or lime+gypsum; this dependence takes place up to 26 or 28 t gypsum ha\(^{-1}\), respectively. Aluminum and potassium were leached in small constant amounts throughout the treatments.

A comparison of the results of the organic matter determination for the Ap horizon in the unamended sample (Fig. 2, column C0) and the same sample following addition of gypsum (column C3) reveals that gypsum decreased the amount of total C that was leached from the profile (the outflows of the first few treatments were colored). The treatment gave rise to a decrease in the content in unhydrolyzed C and hence raised the proportion of humic acids. The addition of lime+gypsum caused no appreciable change in the total C content (Fig. 2); however, it lowers the unhydrolyzed C content relative to the unamended sample; in this case, the proportions of humic and fulvic acids increased to a similar extent.

The addition of gypsum lowered the pH and increased exchangeable Ca levels and the effective cation exchange capacity in all horizons relative to the unamended samples (Table 2). The amount of exchangeable-Al in all horizons after the gypsum amendments diminished in comparison to the unamended samples (Fig. 3, columns C1 and C3). In the Ap horizon the amount of Al extracted decreased with increase the amount of gypsum added; in the other horizons, there was no relationship between those variables. As a result, the Ca\(^{2+}\)/Al\(^{3+}\) ratio was increased, the effect being proportional to the gypsum amount added. Exchangeable Mg was removed in substantial amounts from the Ap horizon and accumulated in the AB and Bt1 horizons.

The addition of lime+gypsum to the Ap horizon increased the pH and Mg, Na, and K losses to a greater extent than the addition of gypsum alone (Table 2); there was no Al-exchangeable extracted (Fig. 3, column C5). Lime had less marked effects on the AB and Bt1 horizons, where the amounts of exchangeable cations (Mg, Na, and K) and the pH were similar and the exchangeable Al decreased in comparison with the unamended samples.
Figure 2. Organic carbon determinations: Total, non-hydrolysed (Unhydr), fulvic (FA), and humic (HA) acids. As a percentage of the whole fraction (≤2 mm). C0 unamended samples; C3 samples treated with 40 gypsum ha\(^{-1}\); C5 samples treated with 17.5 t lime ha\(^{-1}\) +30 t gypsum ha\(^{-1}\).

Table 2. pH, Exchangeable Cation Contents, and Effective Cation Exchange Capacity (CECe) [cmol (+) kg\(^{-1}\)] of the Soil Horizons for Unamended and Amended Samples

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Sample</th>
<th>pH</th>
<th>Ca(^{2+})</th>
<th>Mg(^{2+})</th>
<th>Na(^{+})</th>
<th>K(^{+})</th>
<th>Al(^{3+})</th>
<th>Ca(^{2+})/Al(^{3+})</th>
<th>CECe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap</td>
<td>C0</td>
<td>5.1</td>
<td>0.72</td>
<td>0.25</td>
<td>0.08</td>
<td>0.08</td>
<td>1.67</td>
<td>0.43</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>4.8</td>
<td>1.90</td>
<td>0.12</td>
<td>0.07</td>
<td>0.05</td>
<td>1.48</td>
<td>1.28</td>
<td>3.62</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>4.5</td>
<td>2.70</td>
<td>0.10</td>
<td>0.05</td>
<td>0.03</td>
<td>1.30</td>
<td>2.10</td>
<td>4.18</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>5.9</td>
<td>4.87</td>
<td>0.09</td>
<td>0.04</td>
<td>0.03</td>
<td>0.00</td>
<td>–</td>
<td>5.03</td>
</tr>
<tr>
<td>AB</td>
<td>C0</td>
<td>4.9</td>
<td>0.35</td>
<td>0.12</td>
<td>0.07</td>
<td>0.08</td>
<td>1.48</td>
<td>0.24</td>
<td>2.10</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>4.8</td>
<td>0.65</td>
<td>0.15</td>
<td>0.08</td>
<td>0.12</td>
<td>1.30</td>
<td>0.50</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>4.6</td>
<td>1.15</td>
<td>0.15</td>
<td>0.09</td>
<td>0.10</td>
<td>1.30</td>
<td>0.88</td>
<td>2.79</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>4.9</td>
<td>1.18</td>
<td>0.13</td>
<td>0.09</td>
<td>0.12</td>
<td>0.56</td>
<td>2.11</td>
<td>2.08</td>
</tr>
<tr>
<td>Bt1</td>
<td>C0</td>
<td>4.8</td>
<td>0.77</td>
<td>0.12</td>
<td>0.09</td>
<td>0.10</td>
<td>2.22</td>
<td>0.35</td>
<td>3.30</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>4.7</td>
<td>1.00</td>
<td>0.16</td>
<td>0.08</td>
<td>0.12</td>
<td>1.30</td>
<td>0.77</td>
<td>2.66</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>4.7</td>
<td>1.20</td>
<td>0.18</td>
<td>0.09</td>
<td>0.12</td>
<td>1.30</td>
<td>0.93</td>
<td>2.89</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>4.8</td>
<td>1.15</td>
<td>0.14</td>
<td>0.08</td>
<td>0.12</td>
<td>1.48</td>
<td>0.77</td>
<td>2.97</td>
</tr>
</tbody>
</table>

CECe obtained as KCl extractable acidity + exchangeable Ca, Mg, Na and K.
C0 unamended samples; C1 samples treated with 20 t gypsum ha\(^{-1}\); C3 samples treated with 40 t gypsum ha\(^{-1}\); C5 samples treated with 17.5 t lime ha\(^{-1}\) +30 t gypsum ha\(^{-1}\).
The amount of Al bound to organic matter (extracted by CuCl$_2$ + KCl) before or after the gypsum amendment (Fig. 3) depended on the organic matter content of each horizon. In all horizons, increasing the gypsum application rate increased the amount of Al extracted. In column C5, the addition of 17.5 t lime ha$^{-1}$ +30 t gypsum ha$^{-1}$, resulted in a sharp decrease in the amount of Al extracted from the Ap horizon relative to the addition of gypsum alone. No similar effect was observed on the AB and Bt1 horizons.

It is worth noting the large amounts of sorbed Al (extracted by NH$_4$ acetate) from the unamended samples and from the amended ones (Fig. 3). In the upper horizons (Ap and AB), the amount of Al was greater at a rate of 40 t gypsum ha$^{-1}$; in the Bt1, the opposite was true. The application of
lime + gypsum to the Ap and AB horizons resulted in large amounts of extracted Al relative to the unamended samples and also to those that were supplied with gypsum alone.

In all horizons, raising the amount of gypsum added markedly increased the amount of oxalate-Al extracted (Fig. 3). The addition of lime + gypsum had no effect on the Ap horizon; in the Bt1 horizon, however, the amount of extracted Al was appropriate taking into account that gypsum was added at 30 t ha$^{-1}$ and that lime had no effect on it.

The $\leq$2 mm fraction in the different profile horizons was composed of quartz, phyllosilicates, and hematite (Table 3). The quartz content decreased whereas that of phyllosilicates increased with increasing depth. Hematite was present in a high proportion in the Ap horizon; on the other hand, goethite was present in small amounts in all samples (somewhat greater in the Bt horizons). Traces of feldspars and gibbsite were also detected. The clay fraction ($\leq$2 $\mu$m, Table 3) consisted largely of kaolinite, which increased with depth. Illite and vermiculite were present in proportions of 16 and 17% in the Ap horizon, their contents being smaller (11 and 6%) in the Bt horizons.

The gypsum treatment on the Ap horizon resulted in weaker hematite X-ray diffraction peaks (Fig. 4); this effect was not seen with the lime + gypsum amendment. In the Bt1 horizon, both treatments (gypsum and lime + gypsum) decreased the kaolinite content (Fig. 5). It is important to note that the high amount of Al oxalate obtained for the Ap horizon (unamended sample), which also contained the largest amount of sorbed Al, is not related to the phyllosilicate or hematite content.

Table 3. Semi-quantitative Mineralogical Composition (Relative % Between Samples) of the Soil Profile

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Hor</th>
<th>Q</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Gb</th>
<th>Ph</th>
<th>K</th>
<th>I</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq$2 mm</td>
<td>Ap</td>
<td>37</td>
<td>tr</td>
<td>2</td>
<td>20</td>
<td>tr</td>
<td>38</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>29</td>
<td>tr</td>
<td>4</td>
<td>13</td>
<td>tr</td>
<td>52</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Bt1</td>
<td>19</td>
<td>tr</td>
<td>6</td>
<td>9</td>
<td>tr</td>
<td>64</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Bt2</td>
<td>12</td>
<td>tr</td>
<td>6</td>
<td>12</td>
<td>tr</td>
<td>67</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\leq$2 $\mu$m</td>
<td>Ap</td>
<td>tr</td>
<td>tr</td>
<td>4</td>
<td>6</td>
<td>tr</td>
<td>86</td>
<td>53</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>tr</td>
<td>tr</td>
<td>5</td>
<td>5</td>
<td>tr</td>
<td>88</td>
<td>58</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Bt1</td>
<td>tr</td>
<td>tr</td>
<td>5</td>
<td>4</td>
<td>tr</td>
<td>88</td>
<td>71</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Bt2</td>
<td>tr</td>
<td>tr</td>
<td>4</td>
<td>6</td>
<td>tr</td>
<td>87</td>
<td>73</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

Q quartz, F feldspars, G goethite, H hematite, Gb gibbsite, Ph phyllosilicates, K kaolinite, I illite, V vermiculite, tr traces, – not determined.
In all horizons, increasing the amount of gypsum amendment increased the amount of citrate-extractable Al (Fig. 3). The addition of lime + gypsum had no effect (see column C5, between C1 and C3).

Although in the unamended sample treated with citrate, the vermiculite peaks were absent from the XRD patterns, as a result of the collapse at 10 Å caused by the release of interlayered Al, no relationship between the vermiculite content and the difference between the amount of Al extracted by citrate and oxalate was found.

In the unamended samples, the amount of dcb-extractable Al increased with increasing depth (Fig. 3) and seems to be related to the goethite content, as determined by XRD.

Seed nascence and crop production for *Raphanus sativus* in pots to which gypsum or lime + gypsum amendments were applied (Table 4) were markedly high relative to the unamended pots.

**Figure 4.** X-ray diffraction patterns of the whole fraction (≤2 mm) of the Ap horizon. C0 unamended samples; C3 samples treated with 40 t gypsum ha\(^{-1}\); C5 samples treated with 17.5 t lime ha\(^{-1}\) + 30 t gypsum ha\(^{-1}\). (d-values in nm).
Figure 5. X-ray diffraction patterns of the whole fraction (≤2 mm) of the Bt1 horizon. C0 unamended samples; C3 samples treated with 40 t gypsum ha\(^{-1}\); C5 samples treated with 17.5 t lime ha\(^{-1}\) +30 t gypsum ha\(^{-1}\). (d-values in nm).

Table 4. Effect of the Application of Gypsum and Lime + Gypsum Amendments on Raphanus sativus Growth

<table>
<thead>
<tr>
<th>Treatment in Ap Horizon</th>
<th>Seed %</th>
<th>Root Weight(^a) g</th>
<th>Leaf Weight(^a) g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>35</td>
<td>4.24</td>
<td>8.20</td>
</tr>
<tr>
<td>20 t gypsum ha(^{-1})</td>
<td>65</td>
<td>8.67</td>
<td>19.42</td>
</tr>
<tr>
<td>40 t gypsum ha(^{-1})</td>
<td>70</td>
<td>9.02</td>
<td>23.30</td>
</tr>
<tr>
<td>17.5 t lime ha(^{-1}) +30 t gypsum ha(^{-1})</td>
<td>80</td>
<td>9.70</td>
<td>26.80</td>
</tr>
</tbody>
</table>

\(^a\)Dry per pot.
The application of gypsum or lime + gypsum lowered the level of exchangeable aluminum in soil. This result, however, could not be accounted for the quantitative levels of Al in the outflow solutions, since based on the study of the elements obtained from the treatments and leachates, Al is released in relatively small amounts from the soil. In our opinion, the most likely mechanism for the immobilization of Al could be the formation of a solid phase according to the observations of Pavan et al. (7), O’Brien and Sumner (8) and García-González et al. (9). However, our results contradict those of Oates and Caldwell (10), who found that a substantial amount of exchangeable Al can be removed from the soil if large amounts of gypsum are used and if adequate leaching occurs, possibly because they used very short subsoil columns.

It is well known that Si is leached from soil after gypsum amendments. According to Shainberg et al. (1) and Sumner (2), this occurs because of the decomposition of kaolinite. In this work, gypsum or lime + gypsum treatments cause a loss of Si from the soil columns, and also a decrease in the characteristic peaks for kaolinite in the Bt1 horizon was observed. Both findings support this hypothesis.

Exchangeable Mg in the soil columns was removed from the Ap horizon and accumulated in the AB and Bt1 horizons, consistent with the results of Shainberg et al. (1), who suggested that Mg may be removed from the topsoil and accumulated in the subsoil before it is completely lost.

In some cases (particularly in highly sandy soils), heavy gypsum applications (>5 t ha\(^{-1}\)) have an adverse effect on crop growth, owing to the preferential removal of magnesium from the upper part of the profile with little change in the K status (11). The sandy clay loam texture of our soil probably gave rise to the increased *Raphanus sativus* yield observed. This effect was also found by the addition of 40 t gypsum ha\(^{-1}\).

The loss of organic C, which was detected only after gypsum treatment, is consistent with the results of Belkacem and Nys (12), who attributed it to the competition between organic dissolved carbon and \(\text{SO}_4^{2-}\) anions for positively charged exchange sites.

The gypsum amendment gives rise, in the Ap horizon, to a diminution of the non-hydrolysable C and a increase of the humic acid contents, which produced a greater extracted amount of Al bounded to organic matter than in the untreated sample. Lime + gypsum caused a less marked decreased in unhydrolyzed C than gypsum and results in a extracted proportion of Al bound to organic matter similar to that in the unamended sample, possibly because of the higher pH (5.9) of the samples treated with lime + gypsum relative to those with gypsum alone (pH 4.5). This gypsum amendment causes a marked depolymerization of non-hydrolysable organic compounds. Also, because the amount of organic bound Al extracted following application of lime + gypsum
(column C5) is very similar to that extracted from the unamended sample, the resulting depolymerized compounds can be assumed to contain no Al.

The application of gypsum amendment on the Ap horizon provoked a large decrease in the hematite content. Also, in this horizon, based on the similar amounts of Al extracted with citrate and dcb in the unamended sample, can be assumed that in the hematite lattice no isomorphic substitutions of Fe by Al exists.

In the unamended and gypsum amendment samples the content of sorbed-Al is higher than the exchangeable and organic matter bound Al, which indicates that Al is present mostly as polymeric Al, according to Soon (3) who indicated that extractions with KCl (exchangeable Al) and CuCl2 (organic matter bound Al) provide an estimation of presumably monomeric Al and the subsequent extraction of Al by NH4 acetate at pH 4 (sorbed Al) probably operates through depolymerization of polynuclear hydroxy-Al sorbed on clay or on organic matter surfaces. The addition of lime + gypsum raised the pH and hence resulted in the conversion of monomeric Al into polymeric Al; this action explains why the exchangeable and organic bound Al contents are low and the sorbed Al contents especially high.

Although Oates and Caldwell (10) found no plant response in terms of height or weight to gypsum amendments and leaching, we obtained significantly increased productivity as regards seed nascence and root and leaf dry weight from the gypsum or lime + gypsum treatments. This result is consistent with the results of Noble et al. (13), who achieved improved conditions for root development by increasing the Ca/Al ratio, either through the supply of additional Ca, the reduction of Al activity or both.

CONCLUSIONS

The amount of Al, Na, K, and Si leached following the addition of gypsum and lime + gypsum amendments are very small.

The addition of gypsum causes depolymerization of non-hydrolysable C, which facilitates the extraction of Al bound to organic compounds.

The application of gypsum or lime + gypsum lowers exchangeable Al levels; also, the low proportion of Al in the outflow solutions suggests its immobilization as a solid phase.

Except for exchangeable Al, the gypsum amendment increases the proportion of all Al extracted forms (bound to organic matter, sorbed, oxalate and citrate) relative to the unamended samples. The amount of Al extracted increases as that of gypsum added does.

Gypsum or lime + gypsum amendments increase soil productivity.
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REFERENCES

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