LIME ESTIMATION OF INDONESIAN ACID MINERAL SOILS AND ITS SIGNIFICANCE TO CROP PRODUCTION

by

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1982

RINGKASAN

SLAMET SETIJONO. Perkiraan Kebutuhan Kapur Tanah-Tanah Mineral Masam di Indonesia dan Peranannya dalam Peningkatan Produksi Tanaman (Di bawah bimbingan GOESWONO SOEPARDI sebagai Ketua, ACHMAD MUHAMAD SATARI, ANDI HAKIM NASOETION, OETIT KOSWARA dan HARI SUSENO sebagai Anggota).

Pemberian kapur pada tanah masam merupakan kunci keberhasilan dalam mencapai produksi tanaman yang baik pada tanah-tanah mineral masam. Secara luas telah diakui, bahwa pemberian kapur merupakan usaha terbaik untuk menaikkan pH tanah, meniadakan keracunan aluminium dan mengurangi pencucian hara. Pemberian kapur mempunyai ciri-ciri yang berpengaruh menguntungkan dan merugikan terhadap pertumbuhan dan produksi tanaman. Oleh karenanya, suatu tindakan pencegahan harus dilaksanakan untuk tidak memberikan kapur berlebihan. Setelah tindakan pencegahan tersebut diketahui, kiranya pengaruh yang menguntungkan akan selalu dapat dicapai.

Berkaitan dengan sasaran utama daripada pengapuran tersebut, telah dilaksanakan percobaan-percobaan di laboratorium, di rumah kaca, dan di lapang untuk meneliti berbagai aspek pemberian kapur pada tanah-tanah mineral masam dalam kaitannya dengan peningkatan produksi tanaman di Indonesia.

Tujuan pertama dari serangkaian percobaan itu adalah untuk meneliti hubungan antara pH-tanah dengan perubahan-

perubahan fisiko-kimia dan kimia tanah lainnya sebagai respons pengapuran. Duapuluh delapan contoh tanah mineral masam, berasal dari berbagai lokasi di Jawa Barat, Jawa Tengah, Sumatera Selatan, Sumatera Barat dan Kalimantan Timur, masing-masing diberi 6 taraf $CaCO_3$ murni. Ditambahkan air suling hingga kapasitas lapang, dimasukkan dalam kantong plastik, dan ditempatkan pada suhu kamar selama 30 hari. Selanjutnya diambil contoh tanah sebagian untuk dianalisis. Analisis laboratorium meliputi: $pH_{(H_2O;\ KCl)}$, kemasaman tanah permanen, kemasaman tanah dapat ditukar, aluminium dapat ditukar (Al_{dd}), kejenuhan aluminium, kapasitas tukar kation (KTK), kapasitas tukar kation efektif (KTKE), kejenuhan basa (pH 7.0 dan efektif).

1. Kecepatan perubahan pH-tanah untuk tiap taraf $CaCO_3$ berbeda untuk masing-masing contoh tanah yang diteliti. Kurva pH-$CaCO_3$ menunjukkan bahwa masing-masing tanah memiliki beberapa kisaran kapasitas penyangga; makin tinggi kandungan Al_{dd} makin besar kapasitas penyangganya pada kisaran $pH_{(H_2O)}$ 4.0 - 6.0. Dengan demikian makin banyak jumlah kapur yang dibutuhkan untuk menaikkan pH tanah hingga suatu nilai tertentu.

2. Pemberian kapur hingga $pH_{(H_2O)}$ 5.5 akan menurunkan kemasaman permanen, kemasaman dapat ditukar, kandungan Al_{dd}, dan kejenuhan Al. Proses penurunan berlangsung secara drastik. Makin tinggi kandungan Al_{dd} makin cepat naiknya

kandungan Al atau kejenuhan Al untuk tiap penurunan satuan pH di bawah $pH_{(H_2O)}$ 5.5. Perbedaan akan kandungan Al_{dd} atau kejenuhan Al antara tanah-tanah mineral masam itu akan makin kecil dengan naiknya pH tanah hingga 5.5 atau lebih. Pada $pH_{(H_2O)}$ tanah 5.5 sejumlah 92.5 persen dari kandungan Al_{dd} telah dinetralisasi.

3. Pemberian kapur menyebabkan bertambahnya tapak negatif netto yang aktif dalam proses jerapan. Kapasitas tukar kation dan kejenuhan basa meningkat. Kejenuhan basa yang ditetapkan dengan NH_4OAc pH 7.0 meningkat secara linear dengan meningkatnya pH tanah dalam kisaran taraf $CaCO_3$ yang digunakan dalam penelitian, sedangkan kejenuhan basa efektif meningkat secara asimptotik. Pada $pH_{(H_2O)}$ 5.5 dan 6.0 kejenuhan basa efektif dapat mencapai 82.5 dan 92.5 persen.

Tujuan kedua dari rangkaian penelitian yang dilaksanakan adalah untuk mendapatkan satu atau lebih metode penetapan kebutuhan kapur (KK) tanah-tanah mineral masam berdasarkan ciri-ciri tanah tertentu atau mengadakan perubahan-perubahan daripada metode KK yang menggunakan larutan penyangga. Metode-metode penyangga yang diteliti adalah: (1) SMP-LR-$pH_{6.0}$, (2) SMP-DB-LR-$pH_{6.0}$, (3) Yuan-DB-LR-$pH_{6.0}$. Tingkat ketelitian dari metode-metode tersebut ditetapkan terhadap nilai KK yang diturunkan dari kurva $pH_{(H_2O)}$ - taraf $CaCO_3$ atau kurva $pH_{(H_2O)}$ - taraf $Ca(OH)_2$

masing-masing pada nilai $pH_{(H_2O)}$ 5.5 dan 6.0 setelah berakhirnya masa inkubasi 30 hari (dan 12 bulan). Kebutuhan kapur baku (reference LR test) dinyatakan sebagai $CaCO_3$-LR-$pH_{(H_2O)5.5}$ dan $CaCO_3$-LR-$pH_{(H_2O)6.0}$. Dari kurva pH-taraf bahan kapur telah diturunkan pula $CaCO_3$-LR-$pH_{(KCl)1\ atau\ 2}$ dan $Ca(OH)_2$-LR-$pH_{(H_2O)}$. Sumbangan ciri-ciri tanah terhadap KK dikaji berdasarkan analisis regresi sederhana dan berganda.

1. Bubuk $CaCO_3$ murni maupun bubuk $Ca(OH)_2$ murni sama baiknya untuk menetapkan kebutuhan kapur baku dalam rangka pengujian metode kebutuhan kapur lainnya

2. $CaCO_3$-LR-$pH_{(H_2O)6.0}$ dan $CaCO_3$-LR-$pH_{(H_2O)5.5}$ berkorelasi sangat nyata berturut-turut dengan $CaCO_3$-LR-$pH_{(KCl)1}$ dan $CaCO_3$-LR-$pH_{(KCl)2}$

3. Metode SMP-LR-$pH_{6.0}$ yang ditetapkan menurut Schoemaker, McLean, dan Pratt (1961) pada $pH_{(H_2O)}$ 6.0 berkorelasi sangat nyata dengan $CaCO_3$-LR-$pH_{(H_2O)6.0}$ maupun dengan $CaCO_3$-LR-$pH_{(H_2)5.5}$ untuk tanah-tanah mineral masam dengan kandungan kejenuhan aluminium kurang dari tigapuluh persen. Kebutuhan kapur tanah-tanah mineral masam yang termasuk dalam kelompok ini sebaiknya didasarkan atas persamaan:

(a) untuk menaikkan $pH_{(H_2O)}$ menjadi 5.5

$$KK_{pH_{(H_2O)5.5}}\ (me/100\ g) = -1.34 + 0.71\ SMP\text{-}LR\text{-}pH_{6.6}$$

(r = 0.960**)

(b) untuk menaikkan $pH_{(H_2O)}$ menjadi 6.0

$$KK_{pH_{(H_2O)6.0}} \text{ (me/100 g)} = -0.47 + 0.90 \text{ SMP-LR-pH}_{6.0}$$

$(r = 0.974^{**})$

4. Metode SMP-DB-LR-$pH_{6.0}$ dan Yuan-DB-LR-$pH_{6.0}$ kurang baik untuk digunakan dalam penetapan kebutuhan kapur tanah-tanah mineral masam di Indonesia dibandingkan dengan metode kebutuhan kapur lain yang diuji.

5. Kandungan bahan organik tanah-tanah mineral masam dengan kejenuhan aluminium $<$ 30 persen merupakan penyumbang paling menonjol terhadap kebutuhan kapur tanah bersangkutan, disusul oleh kemasaman dapat ditukar dan kandungan aluminium yang tidak dapat ditukar.

6. Aluminium dapat ditukar (Al_{dd}) merupakan penyumbang yang paling utama untuk tanah-tanah mineral masam dengan kejenuhan Al $>$ 30 persen. Metode SMP-LR-$pH_{6.0}$ kurang baik untuk menentukan kebutuhan kapur tanah yang termasuk dalam kelompok ini. Kebutuhan kapur tanah-tanah ini sebaiknya ditetapkan atas dasar persamaan:

(a) untuk menaikkan $pH_{(H_2O)}$ menjadi 5.5

$$KK_{pH_{(H_2O)5.5}} \text{ (me/100 g)} = 5.71 + 0.70\, Al_{dd} \quad (r = 0.971^{**})$$

(b) untuk menaikkan $pH_{(H_2O)}$ menjadi 6.0

$$KK_{pH_{(H_2O)6.0}} \text{ (me/100 g)} = 7.53 + 0.85\, Al_{dd} \quad (r = 0.974^{**})$$

Tujuan ketiga dari rangkaian penelitian adalah untuk mengadakan kajian tentang respons tanaman jagung (*Zea mays L.*)

terhadap pemberian 6 taraf $CaCO_3$. Respons tanaman dinilai dari produksi bahan kering dan serapan hara. Enam taraf $CaCO_3$ yang diberikan setara dengan 0.00, 0.25, 0.50, 0.75, 1.00 dan 1.25 satuan SMP-LR-$pH_{6.0}$. Jenis tanaman jagung yang dipakai adalah jagung hibrida percobaan 17x16. Tujuh macam tanah mineral masam yang dipilih dari 28 macam tanah dipakai dalam percobaan inkubasi. Bobot contoh tanah untuk tiap taraf $CaCO_3$ adalah setara dengan 1000 g kering mutlak. Setelah ditambahkan kapur, tanah diinkubasi pada kapasitas lapang selama 30 hari dan kemudian ditambahkan pupuk dasar (berbentuk larutan), dan inkubasi dilanjutkan selama 10 hari. Sebelum dipindahkan dalam pot, diambil contoh tanah untuk dianalisis di laboratorium. Hubungan antara respons tanaman dengan perubahan-perubahan ciri kimia tanah sebagai akibat pemberian $CaCO_3$ juga diteliti. Tanaman jagung dipanen 35 hari setelah tanam, bobotnya ditetapkan setelah dikeringkan dalam oven 60^{o} C selama 72 jam dan dianalisis kandungan haranya.

1. Hasil bahan kering tanaman sangat nyata dipengaruhi oleh pemberian kapur. Respons tertinggi dicapai bila pH tanah dinaikkan hingga $pH_{(H_2O)}$ 5.3 dan respons maksimum terjadi pada kisaran $pH_{(H_2O)}$ antara 5.5 dan 6.0.

2. Serapan hara meningkat dengan pemberian $CaCO_3$ hingga taraf yang setara 0.75 SMP-LR-$pH_{6.0}$. Baik hasil bahan kering tanaman, maupun serapan hara menunjukkan penurunan

pada taraf pemberian $CaCO_3$ yang menyebabkan meningkatnya $pH_{(H_2O)}$ di atas 6.0.

3. Hasil bahan kering berkorelasi negatif dengan 10^{-2} $\underline{M}$ $CaCl_2$-Al^{+3}, Al_{dd} atau kejenuhan-Al. Penetapan nilai kritikal menurut Cate dan Nelson (1971) menghasilkan nilai-nilai kritikal berturut-turut: 1.00 ppm Al^{+3}, 0.75 me Al^{+3}/100 g tanah, dan 17.0 persen kejenuhan-Al. Masing-masing nilai kritik ini kiranya dapat dipakai sebagai "pengaman" kebutuhan kapur tanah-tanah mineral masam di Indonesia.

4. Bilamana kandungan (Ca+Mg) dapat ditukar adalah 9.0 me/ 100 g tanah atau nisbah $K/\sqrt{(Ca+Mg)}$ tanah $< 15.3 \times 10^{-2}$ maka paling sedikit 80 persen produksi bahan kering tanaman jagung dapat dicapai.

5. Dengan pemberian $CaCO_3$ setara dengan 0.75 SMP-LR-$pH_{6.0}$ dapat diharapkan adanya peningkatan indeks keefisienan serapan hara rata-rata sebesar 150 persen pada saat tanaman berumur 35 hari setelah tanam; khusus untuk unsur kalsium indeks keefisienan serapannya dapat meningkat hingga 800 persen.

Termasuk dalam rangkaian percobaan rumah kaca, telah pula dilaksanakan percobaan pot untuk meneliti pertumbuhan dan perkembangan akar tanaman jagung (hibrida percobaan 17 x 16) sebagai respons terhadap pemberian berbagai taraf

$CaCO_3$ dan kedalaman pemberian. Latosol dari Darmaga dan Podzolik dari Gajruk digunakan dalam percobaan. Contoh tanah diambil dari lapisan atas (0-30 cm) dan lapisan bawah (30-60 cm). Contoh tanah lapisan atas diberi perlakuan 5 taraf $CaCO_3$, setara dengan 0.00, 0.25, 0.50, 0.75, 1.00 satuan SMP-LR-$pH_{6.0}$; inkubasi adalah 30 hari. Kedalaman pemberian $CaCO_3$ adalah 0-10 cm dan 0-20 cm. Pupuk dasar berupa larutan diberikan 10 hari sebelum tanah dipindahkan dalam pot, dicampur rata dengan agregat tanah setebal 0-10 cm. Contoh tanah bawah (30-60 cm) tidak diberi perlakuan kapur, dan ditempatkan dalam pot pada kedalaman 20-50 cm dan di sebelah atasnya ditempatkan contoh tanah lapisan atas yang telah diperlakukan. Tebal tanah dalam pot seluruhnya mencapai 50 cm dan tanah dalam pot dimampatkan hingga dicapai kerapatan isi 1. Selama percobaan air ditambah secukupnya. Tanaman jagung yang dipakai adalah jagung hibrida percobaan 17x16. Tanaman jagung yang ditanam 5 cm dari tepi pot dipanen pada umur 35 hari dan yang ditanam di tengah-tengah pot dipanen pada umur 45 hari. Pada salah satu sisi pot terdapat jendela kaca untuk dapat mengamati pertumbuhan akar tanaman.

1. Pemberian $CaCO_3$ sangat nyata meningkatkan hasil bahan kering umur panen 35 dan 45 hari. Hasil bahan kering pada pemberian $CaCO_3$ 0-20 cm lebih tinggi dibandingkan dengan pemberian 0-10 cm.

2. Pertumbuhan dan perkembangan akar tanaman jagung pada tanah tanpa perlakuan kapur sangat terbatas pada kedalaman 5 cm. Akar-akar yang dapat menembus lapisan tanah yang tidak diberi kapur menunjukkan gejala keracunan aluminium. Nampaknya dengan intensitas pemberian air bebas ion sebanyak 500 ml tiap hari selama jangka waktu 45 hari kurang pengaruhnya terhadap gerak ion Ca^{+2} ke lapisan tanah yang lebih dalam yang tidak diberikan kapur. Kandungan aluminium dapat ditukar yang relatif tinggi sangat menghambat perakaran tanaman jagung. Pemberian kapur seyogianya dilakukan sedalam mungkin untuk meniadakan "fungsi" penghalang dari aluminium di lapisan tanah sebelah dalam.

Percobaan lapang dilaksanakan untuk meneliti pengaruh pemberian kapur terhadap produksi biji jagung. Percobaan dilaksanakan pada tanah Latosol di Kebun Percobaan Darmaga dan pada tanah Podzolik di Kebun Percobaan Jonggol. Enam taraf pemberian kapur untuk percobaan di Darmaga, setara dengan 0.125, 0.25, 0.50, 0.75, 1.00, dan 1.25 satuan SMP-LR-$pH_{6.0}$, dan bahan kapur yang diberikan adalah batuan kapur kalsitik berukuran 80 mesh dengan nilai $CaCO_3$ setara sebesar 98 persen. Kapur diberikan sedalam 15 cm, dua minggu sebelum tanam. Pupuk dasar yang terdiri atas 100 kg N, 150 kg P, 150 kg K, dan 45 kg Mg/Ha untuk petak seluas 7.5 cm x 5.0 cm dengan disebar rata dan dicampur dengan tanah sedalam ± 15 cm dua hari sebelum tanam. Varietas tanaman jagung yang dipakai adalah varietas unggul H-6, ditanam 20 cm dalam barisan dan 100 cm antara barisan, di mana pada umur 30 hari diperjarang hingga satu tanaman per lobang, atau setara dengan kerapatan 50 ribu tanaman per hektarnya. Satu hari setelah diperjarang, sisa pupuk N yang setara dengan 100 kg N/Ha diberikan menurut larikan sejauh 15 cm dari batang tanaman dan kedalaman $\pm$ 5 cm. Selama percobaan dikerjakan pemberantasan hama dan penyakit dan khusus untuk pencegahan penyakit bulai diadakan perlakuan biji dengan redomil sebelum biji ditanam. Rancangan percobaan adalah rancangan acak kelompok (RBD) dengan 8 ulangan. Percobaan faktorial dilaksanakan pada tanah Podzolik di Jonggol. Perlakuan anak petak adalah 6 taraf pemberian kapur: 0.00, 0.25, 0.50, 0.75, 1.00, dan 1.25 satuan SMP-LR-$pH_{6.0}$. Perlakuan utama adalah 3 taraf pemberian pupuk TSP: 75 kg P, 150 kg P dan 225 kg P/Ha. Rancangan percobaan adalah rancangan petak terbagi dengan 3 ulangan. Macam pupuk dasar yang diberikan 100 kg N, 150 kg K/Ha. Luas anak petak 7.0 cm x 5.0 cm dan jarak tanam 100 cm antara barisan dan 20 cm dalam barisan; jumlah tanaman setara dengan 50 ribu tanaman per hektar. Lain-lain pekerjaan adalah sama dengan apa yang dikerjakan pada Latosol di Darmaga. Tanaman jagung di Darmaga dipanen pada umur 96 hari dan pada Podzolik di Jonggol pada umur 105 hari setelah tanam.

Percobaan lapang pada Latosol di Darmaga dan pada tanah Podzolik di Jonggol menunjukkan bahwa respons hasil jagung pipilan kering terhadap pemberian kapur adalah kuadratik. Hasil maksimum di dua lokasi berturutan dicapai dengan taraf pemberian setara 0.75 dan 0.50 kali jumlah kapur yang ditetapkan dengan uji KK menurut metode SMP-LR-$pH_{6.0}$. Ciri kuadratik daripada respons hasil jagung pipilan kering tersebut adalah selaras dengan respons hasil bahan kering, serapan hara, dan indeks efisiensi serapan hara terhadap taraf pemberian kapur yang sama pada percobaan di rumah kaca. Dengan demikian, sasaran pokok daripada pemberian kapur pada tanah-tanah mineral masam di Indonesia adalah untuk meniadakan keracunan aluminium, sebab aluminium dapat ditukar dalam tanah-tanah tersebut merupakan sumber kemasaman tanah yang utama.

SARAN-SARAN

Tanah-tanah mineral masam diperkirakan meliputi 55.6 juta hektar dengan tingkat kesuburannya adalah rendah hingga sangat rendah. Sebagian besar dicirikan oleh kandungan aluminium dapat ditukar yang tinggi sehingga meracun tanaman. Masukan pupuk saja belum dapat menjamin berhasilnya usaha pertanian tanaman pangan pada tanah-tanah masam tersebut. Oleh karena itu, untuk mensukseskan program pertanian tanaman pangan pada tanah-tanah mineral masam di Indonesia, pemberian kapur seyogianya dapat direalisasi secepatnya. Masukan kapur akan memperbaiki tingkat kesuburan tanah, sehingga masukan pupuk dapat ditingkatkan efisiensinya dan pada akhirnya produksi tanaman meningkat.

Untuk menurunkan kandungan aluminium dari tingkat meracun hingga tidak meracun tanaman dibutuhkan jumlah masukan kapur yang tinggi. Dalam hal ini kita seyogianya tidak perlu cemas, sebab masukan yang tinggi itu hanya diperlukan satu kali saja, yaitu pada saat tanah itu disiapkan untuk usaha pertanian tanaman pangan. Sedangkan untuk selanjutnya masukan kapur sebagai sarana pemeliharaan untuk mengendalikan kandungan aluminium pada tingkat tidak meracun tidak lagi akan mencapai jumlah tinggi dan lagi pula pemberiannya kemungkinan besar tidak tiap tahun tergantung naiknya aluminium sebagai akibat menurunnya pH tanah.

Dalam menyiapkan lahan transmigrasi pada tanah-tanah mineral masam di Sumatera, Kalimantan, Sulawesi, dan di Irian Jaya, masukan kapur sebagai sarana perbaikan kesuburan tanah seyogianya mendapat perhatian yang lebih serius. Masukan kapur itu harus dikerjakan sebelum tanah diserahkan kepada para transmigran.

Pembuatan peta sebaran tanah-tanah mineral masam di Indonesia berdasarkan pH dan sumber-sumber kemasaman tanah, khususnya kandungan akan aluminium dapat ditukar atau kejenuhan aluminium, kiranya akan sangat bermanfaat bagi penyusunan program masukan kapur sebagai sarana perbaikan kesuburan tanah-tanah mineral masam di Indonesia.

ABSTRACT

SLAMET SETIJONO. Lime Estimation of Indonesian Acid Mineral Soils and Its Significance to Crop Production (Under supervision of GOESWONO SOEPARDI as Major Advisor, ACHMAD MUHAMAD SATARI, ANDI HAKIM NASOETION, OETIT KOSWARA, and HARI SUSENO as Members of Advisory and Examining Committee.

Lime application is the key of success in obtaining good crop production on acid soils. There is world wide recognition that liming is the best remedy for aluminium toxicity. Since liming can also have detrimental effects on crop production, if pH levels are raised too high, precautions should be taken not to overlime soils. Once this precaution is taken, beneficial effects from liming will be obtained.

In conjunction with the major goal of determining appropriate levels of liming, laboratory, greenhouse, and field experiments were undertaken to study various effects of liming on soil chemical changes, dry matter yields, nutrient uptake, and corn grain yields. The laboratory experiment was set up to evaluate relationships between soil-pH and other soil chemical changes affected by $CaCO_3$ increments on 28 acid mineral soils. The greenhouse experiment was set up to evaluate dry matter and nutrient uptake by corn plants in response to $CaCO_3$ increments. Relations between dry matter yield response and soil

chemical changes affected by $CaCO_3$ increments were also studied. Seven different acid minerals soils were used in the greenhouse experiment. Field experiments were conducted on a Latosol at Darmaga, and a Podzolic soil at Jonggol to evaluate lime effect on corn grain yields.

Corollary to the major objectives were the needs: (1) to develop a reliable lime requirement test based on selected soil properties or to modify the existing buffer lime requirement methods; (2) to study corn root growth and development in response to lime increments applied to different soil layers in a greenhouse experiment. Two different acid mineral soils were used in the root growth study. After receiving treatment combinations of 6 levels of $CaCO_3$ and two depths of $CaCO_3$ application the top-layer and the unlimed subsurface soil layer were packed in proper sequence in specially constructed boxes to obtain bulk density equal to one. The total height of the soil in each box was 50 cm and consisted of a 0-20 cm top soil layer and a 20-50 cm of subsurface soil. Experimental hybrid corn 17x16 was used in this experiment.

The experimental results support the following conclusions.

1. Liming acid mineral soils to a $pH_{(H_2O)}$ 5.5 resulted in a neutralization of permanent charge acidity and in partial neutralization of pH-dependent charge acidity, resulting in an effective base saturation increases to 82.5 percent.

2. Liming acid mineral soils to a $pH_{(H_2O)}$ 5.0 does not remove potential aluminum toxicity for corn on soils having initial exchangeable aluminum levels above 10.0 me Al^{+3} per 100 g soil.

3. Liming acid mineral soils to a $pH_{(H_2O)}$ 5.5 reduces exchangeable aluminum from potentially toxic to nontoxic levels, regardless the existing differences in aluminum content of the soils.

4. When soil acidity of mineral soils is maintained between $pH_{(H_2O)}$ 5.5 to 6.0 by liming, good plant growth and good crop yield may be obtained.

5. Equations to determine lime requirement to raise the $pH_{(H_2O)}$ of acid mineral soils to 5.5 are as follows:

(a) for soils having Al-saturation less than 30 percent

LR (me/100 g) = $-1.34 + 0.71$ SMP-LR-$pH_{6.0}$ ($r = 0.960^{**}$)

(b) for soils having Al-saturation higher than 30 percent-

LR (me/100 g) = $5.71 + 0.70$ Exch-Al^{+3} ($r = 0.971^{**}$)

6. Equations to determine lime requirement to raise the $pH_{(H_2O)}$ of acid mineral soils to 6.0 are as follows:

(a) for soils having Al-saturation less than 30 percent-

LR (me/100 g) = $-0.47 + 0.90$ SMP-LR-$pH_{6.0}$ ($r = 0.974^{**}$)

(b) for soils having Al-saturation higher than 30 percent-

LR (me/100 g) = $7.53 + 0.85$ Exch-Al^{+3} ($r = 0.974^{**}$)

BIOGRAPHY

The author was born on November 29, 1935 in Kediri. His parents are Tio Poo Sian † and Teng Tjwan Nio †. In 1956 he graduated from Sekolah Menengah Atas Kristen, Malang.

He received the Insinyur Pertanian degree from Fakultas Pertanian, Universitas Indonesia, Bogor in 1963, and a Master of Soil Science degree from University of Wisconsin in 1974.

Since April 1979 he has been a graduate student in the Department of Soil Science at Fakultas Pasca Sarjana Institut Pertanian Bogor.

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He is married to Christiani Suryawidjaja, and they have three children, M. F. Kurniawati, M. A. Dwinita, and M. M. Srihajati.

ACKNOWLEDGEMENTS

The author wishes to express his grateful appreciation to Professor Goeswono Soepardi for his helpdful advice and abiding interest during the course of the investigation, and to the members of his Advisory and Examining Committee, Professors Achmad Muhamad Satari, Andi Hakim Nasoetion, Oetit Koswara, and Hari Suseno.

Appreciation is also expressed to Dr. John T. Murdock for his willingness to be the reader of this manuscript.

The author extends his sincere gratitude to the Rector of Brawijaya University, the Rector of the Institut Pertanian Bogor, the Dean of the Graduate School, the Director of Research and Extension, Directorate General of Higher Education, the Executive Secretary of the Agriculture Consortium, and the Project Director MUCIA/AID, without whose support this study would have not been possible.

Appreciation is also extended to Dr Ir Amris Makmur and his field staff at Darmaga and at Jonggol Experimental Stations, to Dr Ir Yayah Koswara, and to all staff members and laboratory technicians in the Department of Soil Sciences, for the friendship extended to him during his study at Institut Pertanian Bogor.

The author finally wishes to express special thanks to his family for their understanding. Their encouragement, love, and unselfish sacrifice have been a great asset to him.

This study was supported in part by AID Loan 041, and in part by a research grant from International Foundation of Science (IFS), Sweden.

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A thesis submitted to The Fakultas Pasca Sarjana, Institut Pertanian Bogor, in partial fulfillment of the requirement for the Degree of Doctor in Agricultural Science

at

THE FAKULTAS PASCA SARJANA

INSTITUT PERTANIAN BOGOR

B O G O R

1982

Thesis Title : LIME ESTIMATION OF INDONESIAN ACID MINERAL SOILS AND ITS SIGNIFICANCE TO CROP PRODUCTION

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Thesis defended before The Senat Guru Besar, Institut Pertanian Bogor, May 29, 1982 at 11:00 WIB at The Fakultas Pasca Sarjana, Institut Pertanian Bogor.

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INTRODUCTION

Soils of the humid tropics are potentially highly productive, but generally sustain crop yields far below potential levels due to soil acidity. These soils need to be limed and fertilized if their full production potential is to be realized. In Indonesia, more than 50 percent of the 190 million hectares of land area is acid (Satari and Orvedal, 1968). The region encompassing the acid mineral soils tends to have the highest total annual rainfall and the shortest dry season in the country. For this reason, the region comprises the area of highest potential agricultural productivity.

In Indonesia, lime materials and fertilizers are considered costly agricultural inputs. Therefore, the main objective of lime and fertilizer usage is to maximize the return of capital invested in these materials. Optimum return of fertilizers can be obtained if soil acidity, known to be a growth limiting factor, has been eliminated.

Disagreement among scientists as to the relative importance of factors responsible for the low productivity of acid mineral soils throughout the years has not reduced the recognation of the beneficial effects of liming acid mineral soils to crop production (Hartwell and Pember, 1908; Funchess, 1918; Setzer, 1940; Massey, Kang, and Surjatna Effendi, 1964; Sitorus, 1971; Soewandi, 1976; Lathwell, 1979).

The presence of high concentration of aluminum (plus Mn) is toxic to most crops (Lignon and Pierre, 1932; Vlamis, 1953; Adams and Pearson, 1967; McLeod and Jackson, 1967; Arminger, Foy, Fleming, and Caldwell, 1968; Abruna, Vincent-Chandler, Pearson, and Silva, 1970; McLean, Halstead, and Finn, 1972; Lathwell, 1979). Liming is the best remedy to control aluminum and manganese toxicities.

By considering acid mineral soils as a continuum from slightly leached and slightly weathered Mollisols through the progressively more leached and more weathered Alfisols and Ultisols to the highly leached and highly weathered Oxisols, McLean (1971) listed nine potential events to occur when an acid mineral soil is limed. It has also been recognized that not all of the events following liming are beneficial to crops. Under certain conditions, some of them may be detrimental.

Since liming acid mineral soils, especially in the humid tropics, exhibits potential benefits as well as detrimental effects to crop production, and judging from previous results of greenhouse and field experiments, scientists have come to a more solid conclusion that lime requirement (LR) tests which are designed to achieve a soil-$pH_{(H_2O)}$ of 6.4 or higher should not be recommended for tropical acid mineral soils. They have suggested that liming acid mineral soils in the tropics should not exceed a $pH_{(H_2O)}$ of 6.0, because of the potential danger of lime-inducing micronutrient deficiencies and soil structure deterioration (Corey, Ludwick, and Kussow, 1971; Kamprath, 1971; McLean, 1970, 1971; Reeve and Sumner, 1970). Therefore, before attempting to recommend lime for Indonesian acid mineral soils, effects of lime on soil properties and crop responses should be studied. Through these researches a scheme for lime recommendation based on soil properties should be developed for tropical acid mineral soils.

The general objective of this study is to try to determine soil factors that result in positive as well as negative yield response resulting from lime application. The specific objectives of the study are: (1) to relate soil-pH to other soil properties as affected by lime increments; (2) to devise a lime requirement (LR) test based upon one or more selected soil properties; (3) to correlate selected soil properties to crop yield; and (4) to relate base status in soil with crop yield.

Experimental Approach

The properties of acid mineral soils in Indonesia vary widely and can be classified as Inceptisols, Alfisols, Ultisols, or Oxisols. With such a broad range of soils, it is doubtful that any of the existing LR tests can be used for all soils. Successful development of a new LR test or modifying existing LR tests requires *a priori* knowledge of the effects of liming on soil properties known to influence crop growth and production, and also on the nature of crop response to changes in these soil properties.

Samples of acid mineral soils, representatives of areas with the highest potential crop production in Indonesia, were used in these studies. The gerenal approach was to first measure the effects or lime treatments on selected soil properties; $pH_{(H_2O)}$, $pH_{(KCl)}$, titratable acidity (TAc), exchangeable acidity (exch-Ac), exchangeable aluminum (exch-Al^{+3}), extractable aluminum (ext-Al), aluminum saturation (Al-sat), cation exchange capacity (CEC), effective cation exchange capacity (ECEC), and base saturation (BS). This study was followed by observation of crop response to increasing lime increments in the greenhouse. Crop response was measured in terms of dry matter production and nutrient uptake. Plant parameters were then related to known effects of lime on soil properties. The nature of crop response would serve to indicate soil-pH value for optimum crop production. Crop response to lime-induced soil property changes would provide some information for adjusting soil-pH to higher or lower value for crops other than corn (*Zea mays* L.). Relationships between soil-pH and lime levels with soil properties would define factors of prime importance in the development of LR test.

The reliability of some important LR tests, and also those derived from soil properties were evaluated against reference LR tests.

A calibration study was carried out on Latosol and Podzolic soils in West Java.

An additional set of greenhouse experiment was conducted to study corn root growth and development, and dry matter yields in response to lime levels and depth of application.

Working Plans

Incubation Experiment

The purpose of this experiment was to measure the effects of lime application on selected soil properties. Various scatter diagrams and regression analyses were made to show the chemical changes resulting from liming. The standard reference lime requirement (LR) test value of each soil was derived from the corresponding lime rates-soil pH scatter diagram. The reference LR test value was determined at soil-pH$_{(H_2O)}$ of 6.0 and 5.5. The acid mineral soils were equilibrated with various lime increments, incubated at 100 percent field moisture capacity at room temperature. Sub-samples for chemical analyses were taken after 30 days and twelve months incubation period.

Greenhouse Experiment

The greenhouse experiment consisted of two units of pot experiments. One unit was designed to study the effect of lime application on dry matter yield and nutrient availability. These plant responses were related to soil parameters affected by lime increments. Seven soils exhibiting different levels of acidity were used in this experiment. The second unit was designed to study root growth and development, and dry matter yield of corn in response to lime increments and depth of application. Corn, experimental hybrid 17x16 1/, was employed in these greenhouse study.

Field Experiment

Two field experiments were conducted; one on a Latosol on the Darmaga Field Experimental Station, and the other a Podzolic soil on the Jonggol Field Experimental Station. Both field experiments were carried out during the wet season of 1980 - 1981. Corn variety H-6 was employed for these field trials.

1/ The corn, experimental hybrid 17x16 was supplied by Dr.Ir. Yayah Koswara, Department of Agronomy, Institut Pertanian Bogor (IPB).

LITERATURE REVIEW

Sources of Acidity and Their Significance to Lime Requirement

The hydrogen ion activity in the soil solution is a measure of the active acidity in the soil. The amount of acidity present in this form, while important from the standpoint of nutrient availability, is inconsequential when compared to the total acidity. However, the active acidity is usually correlated with total acidity for soils with similar buffering characteristics. This correlation indicates that lime requirement can be assessed by measuring active acidity (Ames and Schollenberger, 1916). However, this procedure is not always successful (Mehlich, 1941, 1942a, 1942b; Keeney and Corey, 1963), because it does not account for the buffering characteristics of different soils.

The capacity factors of soil acidity are much more closely related to the LR than is the intensity factor discussed above. Several capacity factors of acidity have been listed by Tisdale and Nelson (1975, p 420-422), and by Corey et al (1971). The one of them which has a great practical significance is aluminum (Jenny, 1961; Jackson, 1963; Black, 1968; Kamprath, 1970), especially for soils with a $pH_{(H_2O)}$ of less than 5.0, and which are relatively low in organic matter content.

The inorganic sources of acidity have been classified by Jackson (1963) according to acid strength of proton retaining sites (Table 1).

Table 1: Classification of the Inorganic Sources of Acidity According to Acid Streangth of Proton Retaining Sites (Jackson, 1963)

Class	$pH_{(H_2O)}$		Reactant with added base
I	<4.2	(strong acid)	H_3O^+
II	<5.2	(weak acid)	$Al(OH_2)_6^{+3}$
III	5.2 - 7.0	(very weak acid)	$Al(OH)(OH_2)_5^{+2}$
IV	>7.0	(v.very weak acid)	Poly-Al-hydronium

Black (1968) slightly modified the acidity classes as follows: (1) Strong acid, $pH_{(H_2O)}$ 4.2 or less. (2) Weak acids, $pH_{(H_2O)}$ 5.2 or less. In most instances, the hydrated aluminum ions appears to be the only source of acidity that accumulates in large quantities in this range. However, small amounts of hydronium and possibly some hydroxyl groups in the organic matter also contribute. (3) Very weak acids, $pH_{(H_2O)}$ 5.2 to 6.5 or 7.0. Carboxyl groups of organic matter are important sources of acidity in this range, however, edge groups of hydroxy-Al-polymers in interlayer positions and edges of silicate clay particle also contribute to this acidity. Carbonic acids are of minimum importance. (4) Very, very weak acids, $pH_{(H_2O)}$ 6.5 or 7.0 to 9.5. Phenolic groups of organic matter may be significant.

Edge groups of hydroxy-Al-polymers in interlayer positions and edges of silicate clay particles contribute to this acidity. Bicarbonate of calcium and sodium in the soil solution are usually unimportant quantitatively. (5) Extremely weak acids, $pH_{(H_2O)}$ above 9.5. These include alcoholic groups in organic matter, silicic acid, and gibbsite. The first three classes of either Jackson and Black, are the most important in tropical acid mineral soils.

The function of aluminum (and iron) as a source of acidity has been depicted by Corey et al (1971) as follows:

$$|M(OH_2)_6|^{+3} \rightleftharpoons |M(OH)_n(OH_2)_{6-n}|^{+3-n} + n\ H^+$$

$$|M(OH_2)_6|^{+3} \rightleftharpoons |M(OH)_3 + 3\ H^+| + 3\ H_2O$$

where M is Al^{+3} or Fe^{+3}. Aluminum, exchangeable and complexed, is in equilibrium with Al^{+3} in solution, which inturn is in equilibrium with the H^+ ions in solution. Ions in solution are associated with water molecules independendly of one another and, therefore, hydrolytic reactions occur, such as hydrolysis. In the case of Al^{+3}, the process is as follows (Hunt, 1963):

$$Al^{+3} + H_2O \rightleftharpoons |Al(OH)|^{+2} + H^+$$

This implies that an aqueous solution of Al^{+3} ions gives an acidic reaction. The process can continue in an series of reactions as follows:

$$|Al(OH_2)_6|^{+3} \rightleftharpoons |Al(OH)(OH_2)_5|^{+2} + H^+$$

$$|AL(OH)(OH_2)_5|^{+2} \rightleftharpoons |Al(OH)_2(OH_2)_4|^{+} + H^+$$

$$|Al(OH)_2(OH_2)_4|^{+} \rightleftharpoons |Al(OH)_3(OH_2)_3|^{0} + H^+$$

$$|Al(OH)_5(OH_2)|^{-2} \rightleftharpoons |Al(OH)_6|^{-3} + H^+$$

Thus, in acid mineral soil, the concentration of H^+ ions is a function of the rate of hydrolyses of monomeric hexahydronium Al and/or hydroxy-Al (or hydroxy-Fe), whether these ions are adsorbed by clays or organic matter (Coleman and Thomas, 1967).

The addition of a N salt solution, such as N KCl to a soil will displace acid forming cations, mainly aluminum, which is classified as exchangeable aluminum (exch-Al^{+3}) (Lin and Coleman, 1960; Jackson, 1963; Bhumbla and McLean, 1965). Polymeric Al forms, precipitated on clay surfaces (Ragland and Coleman, 1960; Schwertman and Jackson, 1963), or complexed by organic matter (Schnitzer and Skinner, 1964, 1965; McLean, Hourigan, Shoemaker, and Bhumbla, 1964), which can be extracted with NH_4OAc buffered at pH 4.8 following extraction with N KCl, are classified as nonexchangeable acidic-Al by Pionke and Corey (1967). Both forms, exch-Al^{+3} and nonexch-Al, behave differently with soil-pH. At $pH_{(H_2O)}$ 6.3, the concentration of both forms are low, and practically all of the Al is present as $Al(OH)_3$ or other forms that cannot be extracted with ammonium acetate pH 4.8. When the $pH_{(H_2O)}$ decreases to 5.1, the nonexch-Al reaches its apparent maximum and declines rapidly below this pH value. Over the same acidity range, the exch-Al^{+3} increases slowly as the $pH_{(H_2O)}$ is lowered to 5.3, but below this pH value it increases very rapidly at the expense of the nonexch-Al. The nonexch-Al is progressively converted to exch-Al^{+3} below $pH_{(H_2O)}$ 5.1 (Pionke and Corey, 1967). Thus, below $pH_{(H_2O)}$ 5.1, most of the acidic aluminum in the soil is exchangeable. Since many acid mineral soils are highly saturated with Al, the pH measured in this manner is not necessarily the pH of the soil, but that of a dilute aluminum salt solution (Coleman, Kamprath, and Weed, 1959).

The discussion above gives a clear picture of dynamic changes occuring when soil acidity is neutralized with lime. The first ions neutralized from the soil probably are H_3O^+ ions. The second, the most important, is neutralization of exch-Al^{+3} (Plucknett and Sherman, 1963; McLean et al, 1964; Coleman and Thomas, 1967; Hutchinson and Hunter, 1970; Kamprath, 1970; Reeve and Sumner, 1970; Sawhney, Frink, and Hill, 1970). In highly weathered Oxisols, the $pH_{(H_2O)}$ is commonly higher than 4.0. Therefore, liming to soil-$pH_{(H_2O)}$ 5.5 will involve exch-Al^{+3}, partially nonexch-Al, and H^+ covalently bonded to organic matter and clays. Beyond $pH_{(H_2O)}$ 5.5, the latter two sources are primarily neutralized. The trend of neutralization follows the same order of activity of the various forms of soil acidity reported by McLean et al (1972), as follows: Permanent charge H^+ (minor contributor) > exch-Al^{+3} (permanent charge Al^{+3}) > hydroxy-Al monomers > hydroxy-Al polymers > organic matter acidity > lattice Al-OH or si-OH acidity.

The products of a complete lime reaction are exch-Ca^{+2} and/or exch-Mg^{+2}, $Al(OH)_3$, $Fe(OH)_3$, and H_2O, the soil pH measured in water is about 8.3, and complete base saturation is achieved. When acid mineral soils are limed to $pH_{(H_2O)}$ not higher than 6.8 for temperate acid soils, and not higher than 6.0 for tropical acid soils (Corey et al, 1971), a complete neutralization of permanent charge acidity is achieved. However, large amounts of pH-dependent acidity remains (Coleman and Thomas, 1967). Thus, the pH-dependent exchange sites will be only partially opened for cation exchange reaction, primarily Ca^{+2} (and Mg^{+2}), and other cations from the added fertilizers.

Determination of Lime Requirement

Total soil acidity has been shown to be dependent on exchangeable and nonexhangeable forms of aluminum and pH-dependent CEC which arises from organic matter and clays (Keeney and Corey, 1963; Volk and Jackson, 1963; McLean, Reicosky, and Lakshmanan, 1965). Consequently, any determination of total soil acidity or lime requirement must measure the direct or inderect contribution of these factors.

Estimation of Lime Requirement Involving CEC

Many methods for predicting LR include CEC determinations among the variables considered. However, the CEC obtained by a given method is a function of the saturating cation used and the pH of the saturating solution (Broadbent and Bradford, 1952).

The choice of the saturating solution cation is very important, especially if the CEC is determined by titrating a soil to a given pH. The change of pH for each added increment of base appears to be dependent on the position of the saturating cations in the lyotropic series (Li >Na > K >Mg >Ca). Lithium, sodium, and potassium clays, because of hydration effects, are more dissociated than Mg- or Ca-clays; Thus, show higher pH values at the same percent saturation of the CEC sites. When a buffered salt solution is used for saturating the exchange sites, this hydration effect becomes less important. However, extended washing to eliminate excess cations from the system may result in hydrolysis of monovalent cations, and consequently giving low results for CEC. The CEC specific value is arbitrary, since it depends on the pH of the saturating solution (Helling, Chesters, and Corey, 1964).

The selection of any particular pH of the saturating solution is arbitrary, but mostly the saturating solution is buffered at pH 7.0 (Jackson, 1958 p 60). Alexander (1976) advocated the use of a modified Mehlich (1948) barium chloride-triethanolamine ($BaCl_2$-TEA) buffered at pH 8.2 to determine the CEC of soils. Lucas (1942) recommended the use of CEC and pH fo determine LR and indicated that the percent base saturation must be known in addition to the pH of the soil.

In several cases, CEC han been directly correlated with LR without considering the contribution of pH (Keeney and Corey, 1963; Ross, Lawton, and Ellis, 1964). Obviously, such comparison is meaningless unless the soils used are acid and the pH range is restricted, eliminating its contribution to LR.

At present, the use of CEC in estimating LR based on the concepts of percent base saturation and base unsaturation is unpopular, since: (1) percent base saturation does not determine the magnitude of soil acidity, and (2) the increase in percent base saturation or the decrease in base unsaturation may well correlate with pH as different amounts of lime are added; however, the relation does not necessarily exist between soil types (Ross _et al_, 1964). The relationship may vary considerably even among soils of the same origin and degree of weathering (Pierre and Scarseth, 1931). This poor relationship is a result of the different kinds of pH-dependent sites involved.

Other attempts have been made to relate the soil pH to buffering capacity and degree of base saturation through various derivations of the Henderson-Hassebach equation: pH = pK + log salt/acid (Roussopoulos, 1956). However, this Henderson-Hasselbach equation assumes a system with a single pK value, and this will not be the case for soil systems since most acid soils have several buffering ranges and within each buffering range the neutralization curve approaches linearity (Volk and Jackson, 1963). This neutralization curve characteristic suggests the existence of acid sites with many different pK's.

In conclusion, it is apparent that the relationship of pH to percent base saturation is erratic in soil systems where sources of pH-dependent charge are important. Even if those relationships were predictable, their use in estimating LR would be doubtfull since the percent base saturation has been shown to be imperfectly related to total acidity over a wide range of soils.

The pH Depression of Buffered Solutions

A number of LR tests have been developed which relate the pH depression of a buffered solution equilibrated with and acid soil sample to the LR of that soil. Some of these LR tests have achieved popularity within relatively short period of time, and are sufficiently accurate and rapid to show promise as routine laboratory methods.

Woodruff (1947, 1948) proposed the use of calcium acetate, paranitrophenol solution buffered at pH 7.0 for estimating LR. This buffer was calibrated against a clay subsoil so that 0.1 pH unit drop of the equilibrated soil-buffer solution system was equivalent to 1.0 milliequivalent of acidity per 100 g of soil.

The Woodruff's buffer LR test has been shown to predict only 50 percent of the reference LR, though the correlation coefficient was highly significant (McLean, Shoemaker, and Hourigan, 1960; Shoemaker _et al_, 1961; McLean _et al_, 1964). Further study with several temperate acid soils indicated that the Woodruff's LR test underestimated soil with low LR (Keeney and Corey, 1963).

Follwing the Woodruff's buffer LR test was that proposed by Shoemaker _et al_ (1961). The buffer mixture composed of triethanolamine (TEA), paranitrophenol, potassium chromate, calcium acetate, and calcium chloride, buffered at pH 7.5. Its reliability has been tested with the $CaCO_3$-determined LR test at $pH_{(H_2O)}$ 6.8, and proved to be highly correlated (Shoemaker _et al_, 1961; Pratt and Blair, 1962; McLean _et al_, 1964; Ross _et al_, 1964). It showed high coefficient correlation value with the $CaCO_3$-LR-$pH_{(H_2O)}$ 6.5 (Keeney and Corey, 1963), and with the $CaCO_3$-LR-$pH_{(H_2O)}$ 6.0 (Slamet Setijono, 1974).

The other LR tests utilizing a weak buffer solution for predicting LR on poorly buffered acid mineral soils was introduced by Adams and Evans (1962). The buffer solution is composed of potassium hydroxide, paranitrophenol, boric acid, and buffered at pH 8.0. The titration curve of this buffer solution is linear within pH range 6.1 to 6.9; a pH change of 0.10 unit is equivalent to 0.08 milliequivalent acidity per 100 g of soil.

There are two other buffer LR tests that have been introduced in the last decade: (1) the Shoemaker-McLean-Pratt-double buffer LR test (McLean, Ecker, Reddy, and Trierweiler, 1978), and (2) the Yuan double buffer LR test (Yuan, 1974, 1976). Herewafter, both of these LR tests will be designated as the SMP-DB-LR test and Yuan-DB-LR test. Yuan-DB-LR test takes into account both the acidity and the buffering property. The determined acidity from the pH depression of the 20 acid soils used by Yuan (1974) was highly related with the titratable acidity of the supernatant solution and with the $Ca(OH)_2$-determined LR test values. The SMP-DB-LR test is especially useful for soils of low LR where the original SMP-LR test is known to lack desired accuracy.

Among the buffer LR tests which have been developed within the last two decades, the SMP-LR test seem to be the one rapidly gaining favor because of certain advantages over the other LR tests, especially over the Woodruff buffer LR test.

The neutralization curve of the SMP-LR test is linear within the pH range of 4.8 to 7.5. The derived LR test values for three different desired pH's of 6.8, 6.4, and 6.0 were listed in the original paper. This linearity coverage within relatively wide range of pH values is very important for several reasons: (1) due to a longer linear portion, the SMP-LR test exhibits a relatively higher sensitivity for measuring LR than does the Woodruff buffer which is only linear within the pH range 6.0 - 7.0 (McLean et al, 1960); (2) this greater sensitivity reduces the instrumental error associated with the LR measurement; (3) the linear portion encompasses a larger range of LR, meaning that soil-buffered pH values will commonly fall within this linear range, while they will often fall outside the linear range of the Woodruff test; (4) the SMP-LR test is more effective in measuring the aluminum contribution to LR than is the Woodruff LR test (McLean et al, 1960)

Titration and Equilibration of Soil with Bases

Direct titration or equilibration of acid soils with bases provides a fairly accurate measure of LR, but, these tests are time consuming. Therefore, they are not adaptable to routine laboratory analysis.

Early workers equilibrated acid soils with various carbonate compounds and determine the unreacted carbonate by measuring the carbondioxide (CO_2) evolved on addition of a strong acid (Patel and Truog, 1952). Later, following the general use of glass-electrodes for measuring pH, LR was determined by equilibrating acid soil samples with varying amounts of liming material required to raise the soil pH to a desired level. Lime requirement was also determined by titrating acid soils with bases to a predetermined pH value, and by equilibrating acid soils with neutral to alkaline buffers then estimating the LR from the difference in the residual acidity of the buffer as determined by titration.

The laboratory determination of LR which is analogous to the determination of field LR, consists of equilibrating acid soil samples with liming materials. The method is frequently used as a substitute for field-determined LR when checking the accuracy of the other LR tests (McLean _et al_, 1960; Shoemaker _et al_, 1961; keeney and Corey, 1963; Ross _et al_, 1964; McLean, Dumford, and Coronel, 1966; Amedee, 1974; Slamet Setijono, 1974; Yuan, 1974). The determination of LR by titrating a soil sample with a base usually agrees well with the $CaCO_3$-determined LR test.

For titrations of acid soils, the choice of the base is crucial since the use of a strong base may result in side reactions (Kelley, 1926), and the change in pH per unit increment of base added follows the lyotropic series (Baver, 1931).

Other titrimetric mehtods include the use of buffered solutions. The soil is first extracted with the buffered solution and then the extract is titrated to a given end point with an acid or base. These methods have proven to be fairly accurate and rapid for use as LR tests. Schofield (1933) equilibrated acid soils with a lime solution buffered with paranitrophenol at pH 7.1. The extracted solution was then titrated with an acid. The difference between the amount of acid required to titrate the extracted solution and that required for the original buffer was considered to be the LR. In a similar manner, Mehlich (1938) has recommended the use of $BaCl_2$ buffered with triethanolamine at pH 8.2. The Mehlich buffer LR test has been found to be an accurate predictor of the $CaCO_3$-determined LR test (McLean *et al*, 1960; Shoemaker *et al*, 1961).

The basic difference between these LR tests and the more rapid buffer LR tests described in the previous section is that in the titration and equilibration of acid soil with bases, the buffer solution is extracted and titrated to determine LR, whereas in the former the pH of the equilibrium soil-buffer mixture is correlated with LR.

Lime Estimation Based on Soil Properties

It has been established that LR is dependent on permanent H_3O^+ ions, monomeric trivalent aluminum, the pH-dependent sites, the nonexch-Al, and the pH of the soil. In most acid soils the pH-dependent CEC comes from organic matter. Therefore, it is possible to correlate the factors contributing to total acidity to the LR of acid soils. Hopkins, Knox, and Petitt (1903) were unsuccessful in relating active acidity to LR. Ames and Schollenberger (1916) were unsuccessfully in relating exchangeable acidity to LR. Attempts to relate more than one soil property to LR have been more successful. Keeney and Corey (1963), working with Wisconsin soils, and Ross et al (1964), working with some Michigan acid soils, obtained high correlation coefficients of (6.5 - pH)(% OM) with the $CaCO_3$-LR-$pH_{(H_2O)6.5}$. They found that the addition of percent clay to the multiple regression equation did not improve the multiple correlation coefficient enough to warrant including percent clay in determining the LR.

Lime requirement tests based on the measurement of soil properties are usually not accurate predictors of LR of acid soils with a wide range of acid strength or buffering characteristics. One must assume that when predicting LR by measuring combinations of one or more soil properties, the properties measured account for the major portion of the LR over the range of acid soils used. Kamprath (1970, 1972), and Reeve and Sumner (1970) proved that 1.5 x exch-Al^{+3} gave an accurate estimation of LR for acid soils relatively high in exch-Al^{+3}, but found that it underestimated the LR of acid soils which are low in exch-Al^{+3}. The (6.5 - pH)x (% OM) LR test is an accurate LR estimator for soils in which organic matter is the dominant source of acidity, and it will underestimate the LR of acid mineral soils high in exch-Al^{+3} or low in organic matter content.

The Liming Factor

Many people feel that a field trial is the only accurate method of determining LR. One reason for this belief is that LR determined in the field will usually be 1.5 to 2.0 times as high as that determined by $CaCO_3$ or $Ca(OH)_2$ incubation in the laboratory (Shoemaker et al, 1961; Adams and Evans, 1966; Keeney and Corey, 1963). This discrepancy is known as the *liming factor*, and must be accounted for when predicting field LR. The existence of a liming factor is attributed to slow reaction of large sized lime particles and to leaching losses and plant uptake over the several years required for complete equilibration of lime in the field (Russell, 1961 p 530).

Enough work has been done to suggest that part of the liming factor is due to slow reaction rate of some acidic sites in soils. From much of the literature reviewed, it appears that some of these slowly neutralizable sites may be polymeric acidic aluminum. McLean et al (1964) reported that soils equilibrated with lime will reach a miximum pH and then decreases coinciding with the reduction in extractable aluminum content. However, reduction in pH also takes place in the unlimed soil samples suggesting that part of the pH drop is due to the release of salt by docomposition of organic matter.

the acid mineral soils into production with a reasonable degree of success.

Table 2: Estimates of Potentially Arable Land by Soil Groups and Continents 1/

Continent	Highly weathered leached		Percent of total land surface
	Latosol	R.Y. Podzolic	
	(10^6 Ha)		(%)
Africa	417.15	8.10	58
Asia	101.25	36.45	22
Australia	12.15	4.05	11
North America	16.20	76.95	20
South America	514.35	4.05	75

1/ Cited from The World Food Problem (2), vol. II, p 430, and presented in Table 22.4 in Brady, 1974 p 584

In order to establish a successful long-term solution to the food crop production problems on acid mineral soils, the inherent characteristics of acid mineral soils must be understood. From various studies and reviews of moderately to highly weathered leached soils (Pratt and Roberto Alvahydo, 1966; Mohr, van Baren, and van Schuylenborgh, 1972; McLean, 1971; Kamprath, 1971; Zelazny and Calhoun, 1971; Sanchez, 1976; Driessen, Buurman, and Permadhy, 1976; Buurman and Junus Dai, 1976; Buurman, Rochimah, and Sudihardjo, 1976), some of the characteristics can be summarized, see Table 4. The conditions mentioned in point 1 and 3 indicate a high potential for developing rainfed agriculture.

Table 3. Latosol and Podzolic Soils Distribution in Indonesia[1/]

Province	Great Soil Group			Total (Ha)		% acid soil based om	
	Latosol	R.Y.Podzolic	G.B.Podzolic	acid soils	arable land	Province	island
	x 10^3 Ha					%	
West Java	1,569	325	-	1,894	4,625	41	14.3
D.K.I. Jakarta	31	-		31	56	55	0.2
Central Java	763	-	-	763	3,425	22	5.8
East Java	412	-	-	412	4,794	9	3.1
Java and Madura	2,775	325	-	3,100	13,219	-	23.5
D.I. Aceh	388	1,450	100	1,938	5,538	35	4.1
North Sumatera	706	1,931	713	3,350	7,081	47	7.1
West Sumatera	1,100	900	-	2,000	4,975	40	4.2
Riau	62	3,500	244	3,806	9,456	40	8.0
Jambi	881	1,369	-	2,250	4,494	50	4.7
South Sumatera	775	1,700	1,275	3,750	9,844	38	7.9
Bengkulu	756	238	-	994	2,250	44	2.1
Lampung	1,350	1,244	31	2,625	3,725	70.5	5.5
Sumatera	6,018	12,332	2,363	20,713	47,363	-	43.7
West Kalimantan	1,244	2,888	-	4,132	14,675	28	7.6
Central Kalimantan	2,112	2,867	-	4,969	15,262	33	9.2
South Kalimantan	530	237	788	1,555	3,769	41	2.9
East Kalimantan	562	3,977	250	4,789	20,294	24	8.9
Kalimantan	4,468	9,959	1,038	15,465	54,000	-	28.6
North Sulawesi	531	84	-	615	2,675	23	3.2
Central Sulawesi	1,012	200	-	1,212	6,475	19	6.3
South Sulawesi	819	312	169	1,300	6,225	21	6.8
S.E. Sulawesi	287	87	456	830	3,719	22	4.3
Sulawesi	2,649	683	625	3,937	19,094	-	20.7
Maluku	331	2,037	369	2,737	7,475	37	5.5
Irian Jaya	356	7,113	1,593	9,062	42,200	21.5	18.2
Maluku and Irian Jaya	687	9,150	1,962	11,799	49,675	-	23.7
Bali	250	-	-	250	556	45	3.3
NTB	-	-	-	-	-	-	-
NTT	313	-	-	313	4,906	6	4.1
Nusatenggara	563	-	-	563	7,593	-	7.4
I N D O N E S I A	17,160	32,449	5,988	55,597	190,944	-	29.1

1/ Based on plannimetric measurement from tentative map of Indonesia 1976 as a revision of the tentative map 1972, Central Soil Research Institute, Bogor.

Table 4. Climatic-, Physical-, Physico-Chemical-, and Chemical Characteristics of Tropical Acid Mineral Soils (Summaries)

Condition	Description
1. Climatic	Mostly rainy to seasonal, with an average of 9.5-12 months with an average rainfall greater than 100 mm for the rainy region and 4.5-9.5 months for the seasonal region.
2. USDA Taxonomy Class	Latosol and Podzolic soils in Indonesia are mostly belong to Inceptisol and Ultisol. severals belong to Alfisol
3. Physical condition:	
Texture	Loam to clay to heavy clay soils
Structure	Relatively exhibit good structure
Permaebility	poor to excessive drained
Stability	good to excellent structure stability
4. Weatherable minerals	Low to very low in weatherable minerals
5. Clay minerals	Variable amount of montmorillonite, kaolinite, halloysite, vermuculite, 2:1 to 2:1:1 intergrades, hydrated oxides of Fe and/or Al (gibbsite, hematite, goethite, and resistant minerals (quartz, zircon).
6. Charge characteristics	Exhibit permanent as well as variable charge. More intensive weathered will dominated by the variable charge type colloids. The permanent charge is dominated by exchangeable aluminum. Generally have a net negative exchange sites.
7. Acidity	Acid with $pH_{(H_2O)}$ 1:1 ratio below 5.0
8. Effective CEC	Low to high in effective cation exchange capacity. Those with relatively high in ECEC (at soil pH) are primarily due to high in exchangeable aluminum. Generally, have ECEC less than 5.0 me/100 g soil.
9. Leaching lost of nutrient	Low ECEC, coupled with high rainfall and high infiltration rate, will stimulate nutrient lost through leaching. High intensity of rainfall will stimulate soil and nutrient lost through surface runOff on sloping areas.
10. Aluminum content	Contain apprecaible quantity of aluminum. Exchangeable aluminum ranges from as low as 0.05 to as high as 30.00 me Al/100 g soil. Aluminum saturation ranges from less than 1% to 90 %. Generally, the acid mineral soils have Al-saturation on the exchange sites which is toxic to most food crops.
11. Manganese content	Some of the "Latosols" exhibit relatively high in available manganese which is toxic for most food crops
12. Micronutrient	Many of the high leached soils are currently at marginal availability levels of micro - nutrient, mainly zinc.
13. Base status	Medium to very low in base saturation.

Unfortunately, these two "favorable" conditions do not balance the unfavorable properties listed in Table 4.Even with addition of reasonable amounts of NPK fertilizers, food crop production on many of these soils will fail. The presence of toxic concentrations of aluminum (lignon and Pierre, 1932; Vlamis, 1953; Adams and Pearson, 1967; McLeod and Jackson, 1967; Arminger et al, 1968; Abruna et al, 1970; Hutchinson and Hunter, 1970; Evans and Kamprath, 1970; Hoyt and Nyborg, 1971; McLean et al, 1972) and occasionally, the presence of toxic concentrations of manganese (Sherman and Fujimoto, 1946; Morris, 1948; Adams and Wear, 1957; Neenan, 1960; Foy, 1964; Siman, Cradock, Nichols, and Kirton, 1971) are a major limiting factors for optimum crop growth and production. Liming is the best solution to the alleviation of aluminum (and manganese) toxicity and to to the reduction of other unfavorable conditions.

Liming increases the availability of some nutrients and decreases that of others. Liming promotes organic matter decompostition, releasing NO_3^--N to soil solution, making it available to crops or to be leached into deeper soil layers. This increase in available N is at the expense of a reduced total N supply (Scarbrook, 1965). Liming hydrolizes strengite and variscite and releases P ions to soil solution. Liming also reduces the concentration of soluble and exch-Al^{+3} and iron ions which otherwise react with added soluble P to form sparingly soluble Al-P and Fe-P (Black, 1968). Liming increases mineralization of organic-P (Ghani and Aleem, 1942; Halstead, Lapensee, and Ivarson, 1963; Kaila, 1961, 1965). Despite the fact that the immediate benefits of lime application have not been related to increase supplies of Ca (and Mg) (Schmehl, Peech, and Bradfield, 1950), plant growth in acid soils deficient in Ca (and Mg) will receive this additional advantage from liming. Liming increases the availability of both indigenous and fertilizer molybdenum (Bhella and Dawson, 1972). Liming increases the net negative exchange sites. This is due to the fact that: (1) the exchange sites which are previously occupied by Al^{+3} and H_3O^+ ions are opened for exchange reaction; (2) the functional groups which form complex compounds with Al^{+3} ions are active again in exchange reaction; (3) the blocking effect of polymeric hydroxy-Al precipitate in and on clays (deVilliers and Jackson, 1967) is eliminated and become active again in exchange reaction; and (4) deprotonation of H-bonded to clay edges and organic matter increases the net negative sites too. On the other hand, liming decreases the availability of zinc (Camp, 1945; Epstein and Stout, 1951; John, 1972; Shukla, 1972), and copper (Menzel and Jackson, 1940; Peech, 1941) through formation of organo-metal complex (Hodgson, Lidsay, and Trierweiler, 1966). Liming also will decrease the availability of boron (Sims and Bingham, 1968; McPhail, Page and Bingham, 1972).

From the above discussion, one should always keep in mind that liming acid mineral soils in the tropics creates potential benefits as well as potentially detrimetal effects. The detrimental effects generally occur from liming beyoned levels required to gain the benificial effects. When precautions are taken not to lime beyond required levels, the maximum benefit can be achieved. Therefore, liming programs for acid mineral soils in the tropics should be directed toward three major targets: (1) for acid mineral soils having relatively high in exch-Al^{+3}, liming should be directed to neutralization of aluminum (Kamprath, 1970, 1971, 1972; McLean, 1971; Reeve and Sumner, 1970); (2) for acid mineral soils having nontoxic level of Al^{+3}, low in ECEC, and where the exchange sites are dominated by pH-dependent sources (organic matter plus hydroxy-Al or/ and Fe polymers), liming should be directed to pH adjustment. The adjustment of pH in temperate acid mineral soils, where major sources of acidity are pH-dependent, coupled with relatively high unweathered minerals, causes no adverse effects of liming to $pH_{(H_2O)}$ 6.4 or higher (McLean, 1970, 1971). But, for tropical acid mineral soils, liming beyond pH 6.0 may curtail acid weathering or solubilities of compounds so as to cause deficiencies of Mn, Cu, Zn, or B (Corey et al, 1971; Kamprath, 1970, 1971; and (3) liming beyond pH 6.0 is not recommended (Corey et al, 1971; Kamprath, 1970, 1971; McLean, 1971).

MATERIALS AND METHODS

Soils

Twinty-eight acid mineral soil samples were used in an incubation experiment. The first set of greenhouse experiments used seven of these soils, and the second greenhouse study used four soils selected from the 28. The soil samples were collected from different location in West Java, Central Java, South Sumatera, West Sumatera, and East Kalimantan. Twinty-five samples were taken from the top layer (0-30 cm), and the rest were taken from the sub-layer (30-60 cm). Hereafter, they will be assigned code numbers 1 to 28 whenever no descriptive name is given in the text.

The soil samples were air dried, ground and sieved prior to use. Soil aggregates less than 2 mm were used in the incubation experiment, and for chemical analysis. Soil aggregates less than 3 mm were used in the greenhouse experiments. The chemical properties of the 28 soils are tabulated in Appendix Table 1; the average values are presented in Table 5.

Chemical Analyses

The chemical methods used for soil and plant tissue analyses are presented in Table 6. Detailed procedures are given in Appendix B.

Table 5. The Average and The Range Values of the Selected Soil Properties of the Soils Used in Various Experiments

Soil property	average[a/]	range
$pH_{(H_2O)}$, 1:1	4.6	4.0 - 5.4
$pH_{(KCl)}$, 1:1	3.7	3.3 - 4.6
Soil texture,		
sand (%)	8.2	0.3 - 12.3
silt (%)	27.2	7.0 - 48.9
clay (%)	64.6	18.5 - 92.5
C-organic (%)	2.06	0.78 - 4.04
Total N (%)	0.20	0.19 - 0.29
Exch-Cations (me/100 g),		
Na^+	0.14	0.04 - 0.86
K^+	0.21	0.06 - 0.59
Ca^{+2}	2.88	0.45 - 17.16
Mg^{+2}	2.05	0.04 - 10.19
Al^{+3}	5.88	0.06 - 28.82
TAc (me/100 g)	7.15	0.22 - 30.88
Exch-Ac (me/100 g)	11.13	5.87 - 21.46
CEC (me/100 g)	24.73	8.85 - 49.51
ECEC (me/100 g)	12.36	3.46 - 32.58
Base saturation[b/] (%)	18.0	4.3 - 39.9
Base saturation[c/] (%)	52.3	5.2 - 99.0
Al-saturation (%)	38.1	0.2 - 88.5
Ext-Al (me/100 g)	12.83	2.90 - 38.24

a/ Average of 28 soils used
b/ Calculated based on CEC
c/ Calculated based on ECEC

Estimation of Field Moisture Capacity

Field moisture capacity (FMC) was determined according to the following procedure. A known quantity of air dried soil aggregates was placed in a paralon cylinder having an inner diameter of 5.0 cm and height of 20 cm. Distilled water was then added until a wetting front of about 12.5 cm was observed. The top of the cylinder was sealed with a piece of plastic sheet to prevent evaporation, and the cylinder was stored at room temperature. After 3 days, the middle portion of the moist soil was removed and its moisture content determined by lost of weight upon drying in an oven at 105^{o} C for 48 hours.

Incubation Experiment

The 28 soil samples were equilibrated with 6 levels of pure reagent grade $Ca(OH)_2$ or $CaCO_3$ powder. The amount of lime material needed to achieve soil-$pH_{(H_2O)}$ 6.4 as determined by the SMP-LR-$pH_{6.4}$ (Shoemaker et al, 1961) was assigned as the 1.00 SMP-LR-$pH_{6.4}$ unit. The other five levels were: 0.00, 0.25, 0.50, 0.75, and 1.50 SMP-LR-$pH_{6.4}$ units (Appendix Table 2 column 4). The amount of $Ca(OH)_2$ or $CaCO_3$ required for each level was mixed with 500 g soil aggregates. Distilled water was added to wet to 100 percent field moisture capacity, and the moist limed soil aggregates

Table 6. Chemical Methods Used for Soil and Plant Analyses[a/]

Analysis	Method	Reference
1. Soil:		
$pH_{(H_2O)}$ or $pH_{(KCl)}$	1:1 ratio; shaken 5 min	Anonymous, 1981
Soil Texture	Pipette method using Na-pyrophosphate as dispersing agent	Kilmer and Alexander, 1949
CEC	NH_4OAc pH 7.0 extraction titration with std. NaOH	Anonymous, 1981
ECEC	NH_4OAc determ. bases plus TAc	A.S.F. Juo (ed.). 1979.
C-organic	Walkley and Black method	-"-
Total N	Macro Kjeldahl method	-"-
TAc	N KCl, 1:10 ratio, titration with std. NaOH	Anonymous, 1981
Exch-Ac	$BaCl_2$-TEA buffered at pH 8.0. Modified method of Alexander	Alexander, 1976
$Exch\text{-}Al^{+3}$	N KCl extraction, 1:10 ratio, shaken 30 min, and Al in aliquot determ. by Ferron method	Rainwater and Thatcher, 1960
Ext-Al	NH_4OAc pH 4.8, 1:25 ratio, Al in aliquot determ. by Ferron method after treatm. with agua regia	Slamet Setijono, 1974
Exch-bases	NH_4OAc pH 7.0 extract, 1:20 ratio. Na and K by flame photometer, Ca+Mg by EDTA titration after aqua regia treatment	Chapman and Pratt, 1961
2. Plant Tissue:		
Dry Ashing	I.I.T.A. Selected Method	A.S.F. Juo (Ed.). 1979.
P	by Vanado-molybdate	
K	by Flame photometric	
Ca, Mg, Mn, Zn, Cu	by Atomic Absorption	
Fe, and Al	by Ferron method	

a/ Detailed description of the chemical procedures were given in Appendix B was put in a plastic bag and tightly sealed to inhibit evaporation without unduly inhibiting diffusion of O_2 and CO_2 gas. The plastic bags with soil were kept at room temperature during the entire period of the experiment. After 30 days incubation, a sub-sample was taken from each bag for chemical analyses. The chemical analyses included: $pH_{(H_2O)}$, $pH_{(KCl)}$, TAc, exch-Ac, exch-Al^{+3}, exch-bases, exchangeable-H^+, ECEC, base saturation, Al-saturation, and Al-neutralization.

The relationship between soil-pH and the other soil properties being affected by lime application is presented in the form of scatter diagrams.

The reference LR test value of each soil used in the incubation experiment was calculated from the corresponding $pH_{(H_2O)}$- lime curve at two predetermined $pH_{(H_2O)}$ values of 5.5 and 6.0. The reference LR tests were designated as the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and the $CaCO_3$-LR-$pH_{(H_2O)5.5}$. The corresponding $CaCO_3$-LR-$pH_{(KCl)1}$ and $CaCO_3$-LR-$pH_{(KCl)2}$ were also derived. The average value of the difference between pH measured in distilled water and that in N KCl of each soil receiving different levels of lime was calculated; this value was then substracted from 6.0 or 5.5, and the result was used as the predetermined $pH_{(KCl)}$ in calculating the $CaCO_3$-LR-$pH_{(KCl)1,2}$ from the $pH_{(KCl)1 \text{ or } 2}$- lime curves.

The Prediction of Lime Requirement

The Buffer Methods

The selected buffer methods were: (1) the SMP Buffer Method (Shoemaker et al, 1961), (2) the SMP-Double Buffer Method (McLean et al, 1978), and (3) Yuan's Double Buffer Method (Yuan, 1974, 1976). All the buffer methods were based on a desired $pH_{(H_2O)}$ of 6.0. Hereafter, they are referred to as SMP-LR-$pH_{6.0}$, SMP-DB-LR-$pH_{6.0}$, and Yuan-DB-LR-$pH_{6.0}$

Lime Estimation Based on Soil Properties

The soil properties used in this study were derived from the original chemical data presented in Appendix Table 1. Simple correlation analyses and multiple regression by the forward selection procedure (Kleinbaum and Kupper, 1978 chapt. 15) were carried out to evaluate soil properties contributing to LR of the acid mineral soils. The soils were classified into two groups based upon the amount of exch-Al^{+3} contents.

Greenhouse Experiments

The First Unit Experiment

Seven different acid soils were used in this experiment. Each soil received 6 levels of pure reagent grade $CaCO_3$ powder. The amount needed to achieve $pH_{(H_2O)}$ 6.0 was based on the $SMP\text{-}LR\text{-}pH_{6.0}$ and was assigned as the 1.00 $SMP\text{-}LR\text{-}pH_{6.0}$ unit. The other 5 levels were: 0.00, 0.25, 0.50, 0.75, and 1.25 $SMP\text{-}LR\text{-}pH_{6.0}$ units (Appendix Table 3 column 2-3).

Air dried soil aggregates, equivalent to 1000 g 105°C oven dry, was mixed with the specific amount of lime, placed in a plastic bag, brought to 100 percent FMC with distilled water, closed tightly with a rubber band, and kept at room temperature for 30 days. After 30 days, the soil was air dried and basal nutrient solution was sprayed onto the soil aggregates. The basal nutrient mixture is listed in Table 7. After the basal nutrient application, the soil

Table 7. The Composition and Concentration of Basal Nutrient Solution

Element	Carrier	Conc. in 200 ml volume (ppm)
N	NH_4NO_3	200
P	H_3PO_4	100
K	K_2SO_4	150
Mg	$MgSO_4$	10
Zn	$ZnSO_4$	10
Cu	$CuSO_4$	6
B	H_3BO_3	0.9
Mo	H_2MoO_4	0.9

was brought to 100 percent FMC again, and incubated for additional 10 days. Prior to putting it in a 1.0 kg capacity plastic pot, a sub-sample was taken for analysis. The results of the chemical analyses are tabulated in Appendix Table 3. The test crop, corn (*Zea mays* L.), experimental hybrid 17x16 was planted four seeds per pot, and thinned to three plants after emergence. The seeds were planted 2 cm deep. All pots were rotated at random twice a week, and watered daily to maintain the moist soil at 100 percent FMC during the entire period of the experiment. The experimental design used was a completely random design (CRD) with three replications. The corn plants were harvested at 35 days after planting, oven dreid at 60-65^{o}C for 72 hours, weighed and ground in a Wiley cutting mill having stainless steel blades, and a 40 mesh sieve. The plant tissue was then saved for further chemical analyses.

The Second Unit Experiment

Square boxes lined with black plastic sheet were made of 9 mm plywood. The boxes had an upper diameter of 25 cm and a bottom inner diameter of 20 cm, and were 60 cm deep (Figure 1). They were packed with sub-layer soil aggregates to depth of 20-50 cm, and with top-layer soil aggregates to depth of 0-20 cm. The soil aggregates were packed to a bulk density of 1.0. The toplayer of soil aggregates received a factorial combination of treatments before they

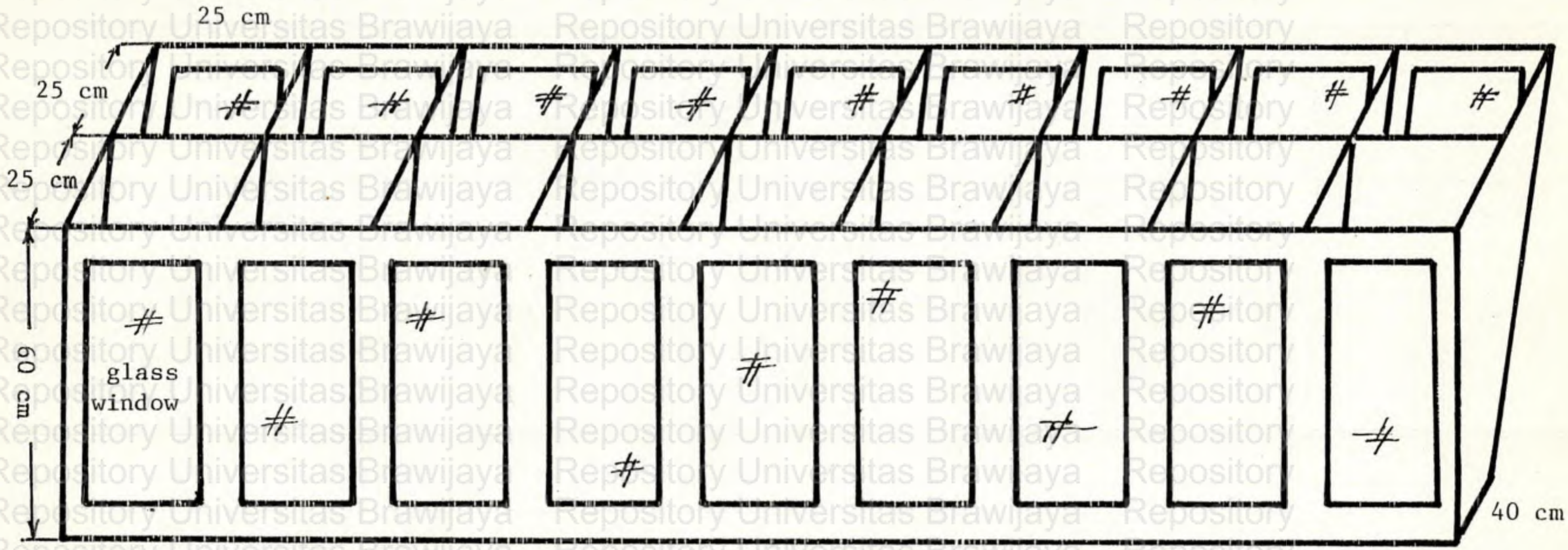

Figure 1. The Design of Locally-made Pots For Greenhouse Experiment-II
It was made of 9 mm plywood with glass window on one side of each pot, and at the center of the bottom side a hole was made for leachate water

placed in their respective pots. The factorial combinations were: L_1D_1, L_1D_2, L_2D_1, L_2D_2, L_3D_1, L_3D_2, L_4D_1, L_4D_2, where L_{1-4} represents $CaCO_3$ levels, equivalent to 0.25, 0.50, 0.75, and 1.00 SMP-LR-$pH_{6.0}$ unit respectively; D_1 and D_2 represent depth of $CaCO_3$ application of 0-10 cm and 0-20 cm. A randomized block design arrangement was used with three replications.

The $CaCO_3$ treated soil aggregates were incubated at 100 percent FMC in a tightly sealed plastic bag at room temperature for a period of 30 days. The incubated soil was then air dried, and the basal nutrient solution was evenly sprayed onto th soil aggregates (Table 8). An Incubation of 10 days

Table 8. The Composition and Concentration of Basal Nutrient Solution

Element	Carrier	Conc. in 200 ml volume (ppm)
N	NH_4NO_3	200 1/
P	H_3PO_4	200
K	K_2SO_4	200
Mg	$MgSO_4$	15
Zn	$ZnSO_4$	10
Cu	$CuSO_4$	6
B	H_3BO_3	10
Mo	H_2MoO_4	0.9

1/ 100 ppm N was applied as basal nutrient. The other half (100 ppm N) was applied at 30 days after planting.

was then carried out at 100 % FMC. Finally, the treated soils were put into their respective pot.

Two soils with different acid strengths were used in the second greenhouse experiment: a Reddish Brown Latosol and a Red Yellow Podzolic. The Latosol was taken from a previously unlimed rubber nursery site at the Darmaga Experimental Station, and the Podzolic soil was taken from an uncultivated area near Gajruk village. Present vegetation is mainly *Melastoma sp.* and *Imperata cylindrica*.

The plant indicator was an experimental hybrid of corn, 17x16. Four seeds were planted per pot; two seeds 5 cm from the glass window, and two seeds in the center of the pot. After emergence, they were thinned to one plant per hole. Prior to planting the seeds, dionized water was added at rate of 250 ml per minute until a waterfront at 20 cm was observed through the glass window. During the entire experimental period, 500 ml of deionized water was added daily. The water was sprayed 5 cm above the soil surface, and allowed to move downwards by gravity. Within 3 days after planting, water reached the bottom, and the excess water was permitted to leach out through the bottom hole. The corn plants near the glass window were harvested 35 days after planting and those at the center were harvested 10 days later. The corn plants were oven dried at 60-65^{o}C for 72 hours, and weighed.

During the course of the experiment, root growth and development were visually observed through the glass window. The glass windows were covered with a black plastic sheet when not under observation. At the end of the 45 day period, the glass windowed side was opened, soil aggregates were removed from the root surfaces by gentle tapping and a gentle tap-water spraying. Several pictures were then taken.

Field Experiments

The field experiments were conducted on a Latosol from Darmaga and on a Podzolic soil from Jonggol. The two soils have different soil properties (Appendix Table 4). Detailed procedures are outlined in the following sections.

Field Experiment on the Latosol from Darmaga

Different levels of calcitic limestone (80 mesh), equivalent to 0.125, 0.25, 0.50, 0.75, 1.00 and 1.25 SMP-LR-$pH_{6.0}$ test values were used. The lime material was broadcast on 7.5 m x 5.0 m plots, and mixed with the top 15 cm of soil using a small rototiller hand-tractor. Eight replications of each lime treatment, laid out in a randomized complete block design arrangement were used. The liming material was applied two weeks prior planting. In addition, basal fertilizers composed of 100 kg N, 250 kg P, 150 kg K, and 45 kg Mg per hectare in the form of urea, TSP, K_2SO_4 and $MgSO_4$, respectively, were applied. The basal fertilizers were broadcast, mixed with the soil to a depth of 15 cm with a small rototiller hand-tractor. A high yielding corn variety H-6 was hand planted in rows 100 cm apart running east and west. Three redomil-treated seeds were spaced 20 cm apart in the row and later thinned to one plant per hill 30 days after emergence, and one day before the application of the second half of the N (100 kg/Ha). The final population was 50 thousand plants per hectare.

During the first weeks of the growing period, the corn plants were sprayed with insecticide (Basodin 60) at the recommended rate at two days interval. The rest of the growing period, the corn plants were sprayed with Basodin 60 or Thiodane at much longer intervals. The corn plants were harvested at 96 days after planting, 9 days ealier than it had been planned, because of strong wind and thunder stroms during the last two weeks on the previously planned schedule.

Field Experiment on Podzolic Soil from Jonggol

The experimental layout was 6 x 3 factorial arranged in a split-plot design with three replications. The experimental plot area was 7.0 cm x 5.0 cm. The main-treatment was P, applied at three levels: 75, 150, and 225 kg P per hectare. The sub-treatment was lime with six levels, equivalent to 0.00, 0.25, 0.50, 0.75, 1.00 , and 1.25 SMP-LR-$pH_{6.0}$ test values. The lime material was 80 mesh calcitic limestone. Both treatments were broadcast over the entire 7.0 cm x 5.0 cm plot and mixed in the top 15 cm of soil with a large hoe. In addition, basal fertilizers, consisting of 100 kg N and 150 kg K per hectare were added. The second treatment of N (100 kg N/Ha) was applied at 30 days after planting the corn seeds (high yielding variety H-6) or one day after thinning to one plant per hill. The calcitic limestone was applied two weeks before planting. The P fertilizer plus the basal fertilizers were applied two days before planting. The plant protection procedure used was the same as that of the Darmaga field experiment.

RESULTS AND DISCUSSION

The Effect of Lime on Selected Soil Properties

The selected soil properties were: pH, titratable acidity, exchangeable acidity, exchangeable aluminum, aluminum saturation, base saturation, cation exchange capacity, and effective cation exchange capacity. The selected properties were determined on samples which had been incubated with different levels of lime for 30 days. The results are tabulated in Appendix Table 2.

Soil-pH$_{(H_2O)}$ and Soil-pH$_{(KCl)}$

Soil pH changes as affected by $CaCO_3$ increments are tabulated in Appendix Table 2 column 4 and 5. Some of these lime rate-soil pH relationships are presented in Figure 2. The circled numerical figure at the end of each curve represents the soil code number. Different acid strength or buffering capacities are observed among the soils. The general forms of the buffering curves are the same as those reported by McLean et al (1960), Pratt and Roberto Alvahydo (1966). The buffering curves indicate that the 28 soils exhibit several buffering ranges within the $CaCO_3$ levels used in the experiment. According to Volk and Jackson (1963) descrete buffering zones are visible in most of acid soils. Working with H-resin treated montmorillonite plus $AlCl_3$, Volk and Jackson (1963) uncovered four distinct buffering ranges which had been attributed to hydronium monomeric

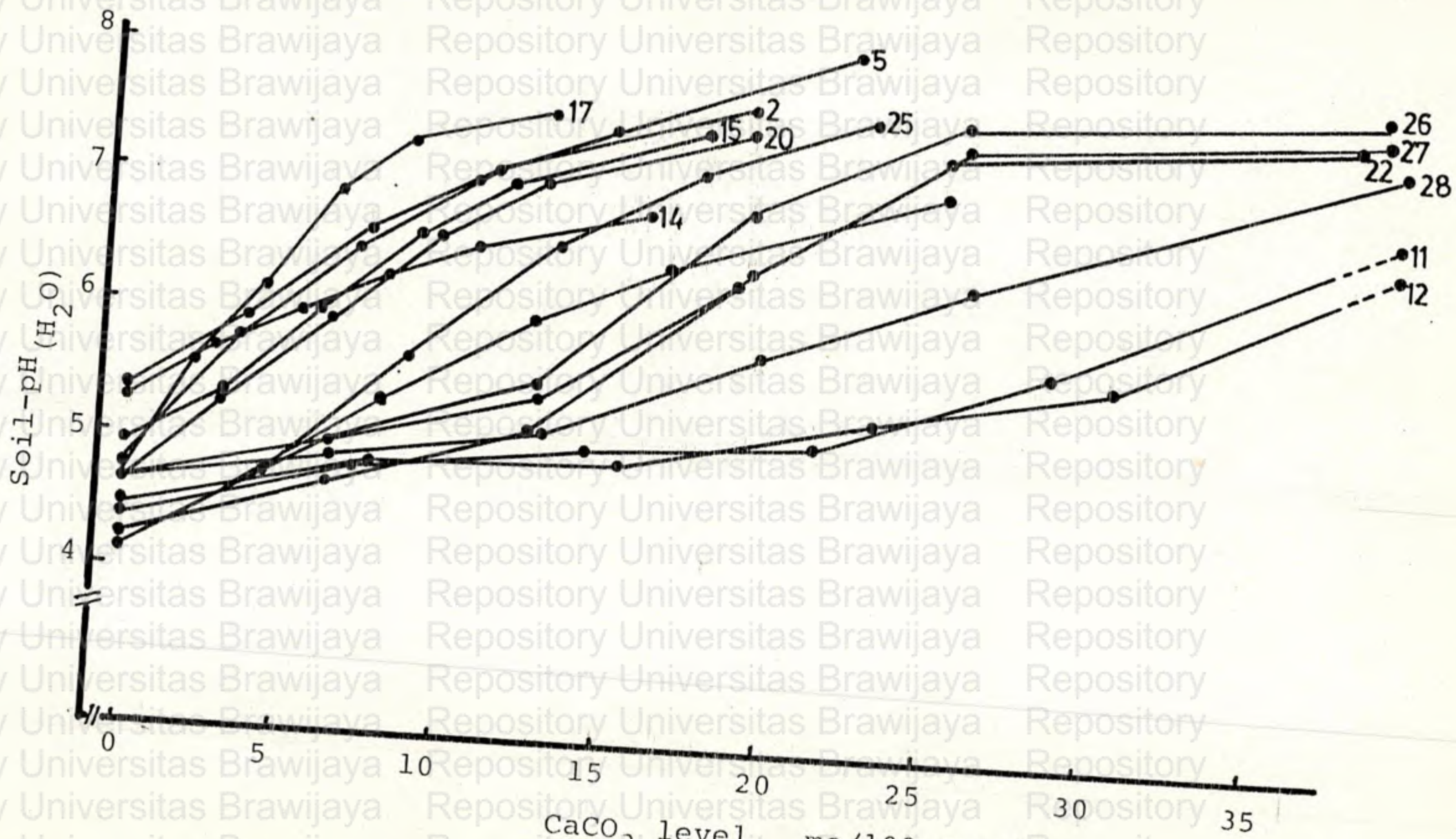

Figure 2. The Effect of $CaCO_3$ Application on Soil-pH

tirvalent aluminum, polymeric hydroxy aluminum, and other pH-dependent charges. Within the pH range obtained in this experiment, all sources of acidity (Jackson, 1963; Black, 1968) made important contribution to the acid strength of the soils. The pH data presented in Appendix Table 2 column 4 and 5 show that when the $pH_{(H_2O)}$ is substracted from the $pH_{(KCl)}$ a negative value is obtained. With increasing $CaCO_3$ increments the negative differences tend not to decrease. Thus, during the 35 day incubation period, there was no significant effect of salt. Either means of measuring soil pH in distilled water or N KCl, can be used to determine the $CaCO_3$-LR test, though for temperate acid mineral soils $pH_{(KCl)}$ is preferred (Keeney and Corey, 1963). When the average value of the negative differences between $pH_{(H_2O)}$ and $pH_{(KCl)}$ values is correlated with the corresponding exch-Al^{+3} of the $CaCO_3$-untreated sample, a highly significant correlation coefficient is obtained ($r = 0.894^{**}$, $n = 28$), indicating that the higher the difference between $pH_{(KCl)}$ and $pH_{(H_2O)}$ the more important is the exch-Al^{+3} as source of acidity (Julian Velez and Blue, 1971), and the higher the LR of the particular soil. The negative difference, $pH_{(H_2O - KCl)}$, indicates that the 28 soils exhibit net negative charge at their existing soil pH values, and their zero point of charge (ZPC) should be below these natural pH values (Uehara and Keng, 1975; Morais, Page, and Lund, 1976; Gallez, Juo, and Herbillon, 1976; Parker, Zelazny, Sampath, and Harris, 1979).

Titratable Acidity (TAc)

The determined titratable acidity of the soils in response to $CaCO_3$ increments is tabulated in Appendix Table 2 column 6. Calcium carbonate treatment reduced TAc drastically in the first two $CaCO_3$ increments. The relationship with soil-pH is curvilinear. The components of TAc are exch-Al^{+3} and exch-H^+ (Coleman, Weed, and McCracken, 1959). The higher the exch-Al^{+3} the faster was the rate of TAc reduction. The exch-H^+ contributes only a small fraction to the TAc of the soils (Appendix Table 2 column 11).

Exchangeable Acidity (exch-Ac)

The rates of change of exch-Ac with pH as both soil properties were affected by $CaCO_3$ application are tabulated in Appendix Table 2 column 13 and in Figure 3. The arabic number at the begining of each curve indicates the soil code number. Some of the relationships between soil $pH_{(H_2O)}$ and exch-Ac were not shown in Figure 3 because they superimposed on those presented. The negative rate of exch-Ac reduction with increasing $CaCO_3$ increments is either linear or curvilinear, depending on the exch-Al^{+3} content of each soil studied. Those which exhibit relatively high levels of exch-Al^{+3} showed curvilinear relationships, and the inflection points are within soil-$pH_{(H_2O)}$ range value of 5.5 to 6.0; below this arbitrary inflection point, the rate of

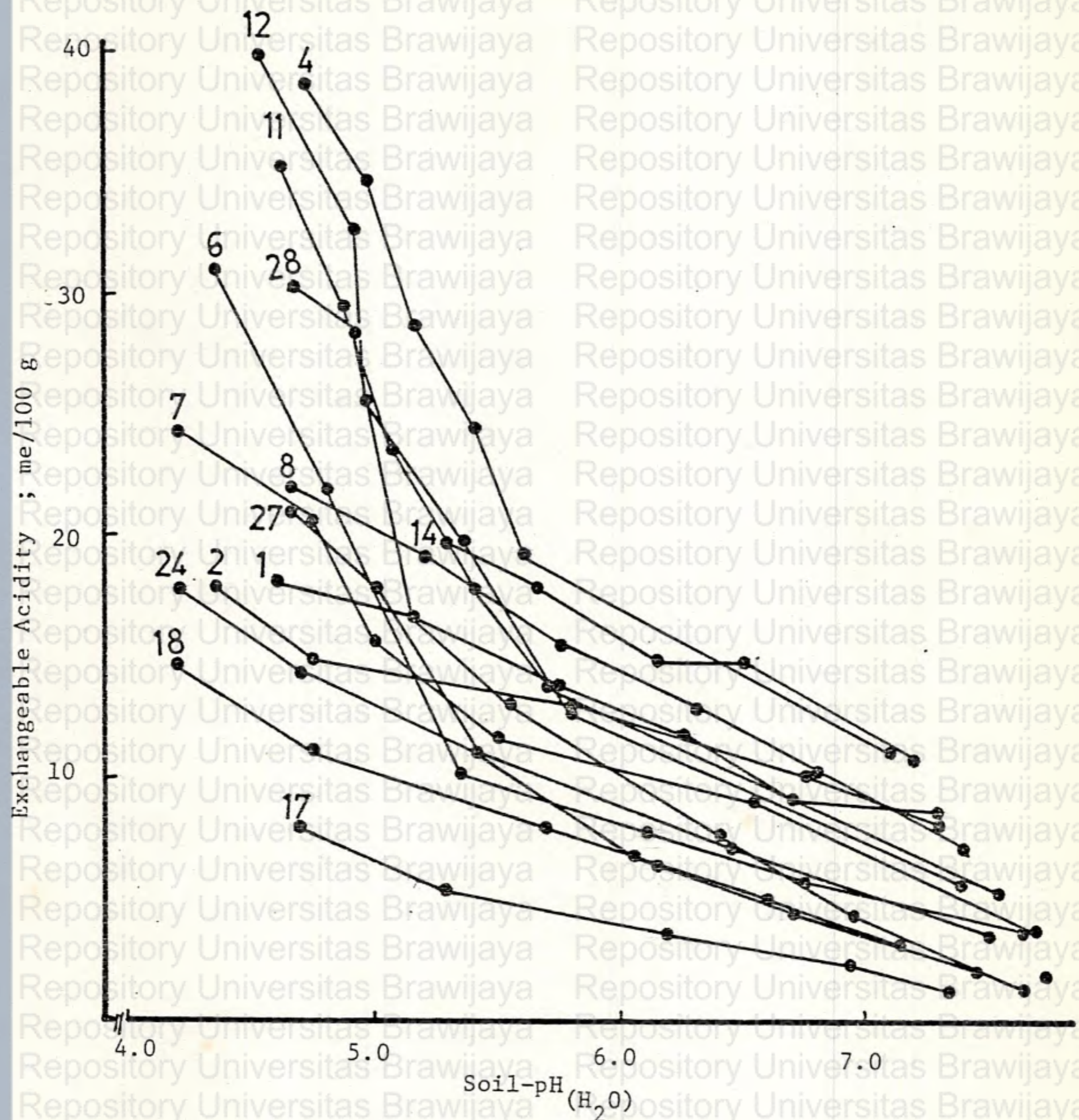

Figure 3. The Relationship between Soil-pH and Exchangeable Acidity as Affected by $CaCO_3$ Application

exchangeable acidity reduction with liming is higher when the exch-Al^{+3} content of the soil is higher. This implies that exch-Al^{+3} plays an important role in determining the rate of neutralization of exch-Ac of the soils below $pH_{(H_2O)}$ of 5.5. It is interesting to note further that when the titratable acidity value is subtracted from the corresponding exch-Ac value, several of the soils having relatively high levels of exch-Al^{+3} resulted in a negative value in the first 2-3 $CaCO_3$ increments, indicating that axch-Al^{+3} did not react with the $BaCl_2$-TEA buffer solution. This fact was also observed by Shoemaker <u>et al</u> (1961). According to Shoemaker <u>et al</u> (1961), when $CaCO_3$ is added to moist soil, the $CaCO_3$ reacts slowly with Al^{+3} ions causing only gradual change in pH (see Figure 2 code numbers 11, 12, and 28). Under these conditions, all the exch-Al^{+3} would eventually be replaced from the exchange sites, reacting quantitatively with the added $CaCO_3$. In contrast, when $BaCl_2$-TEA buffer solution is added to the soil sample, there is an instanteneous change in pH, which may cause a major portion of the unreacted Al^{+3} to be trapped inside the clay lattice, giving rise to the negative values.

Exchangeable Aluminum (exch-Al^{+3})

The values of exch-Al^{+3} of the soils in response to calcium carbonate application are tabulated in Appendix Table 2 column 10. The relationship of exch-Al^{+3} to the corresponding $pH_{(H_2O)}$ changes is presented in Figure 4. The exch-Al^{+3} decreases with increasing pH. The negative curvilinear characteristics and the drastic change which

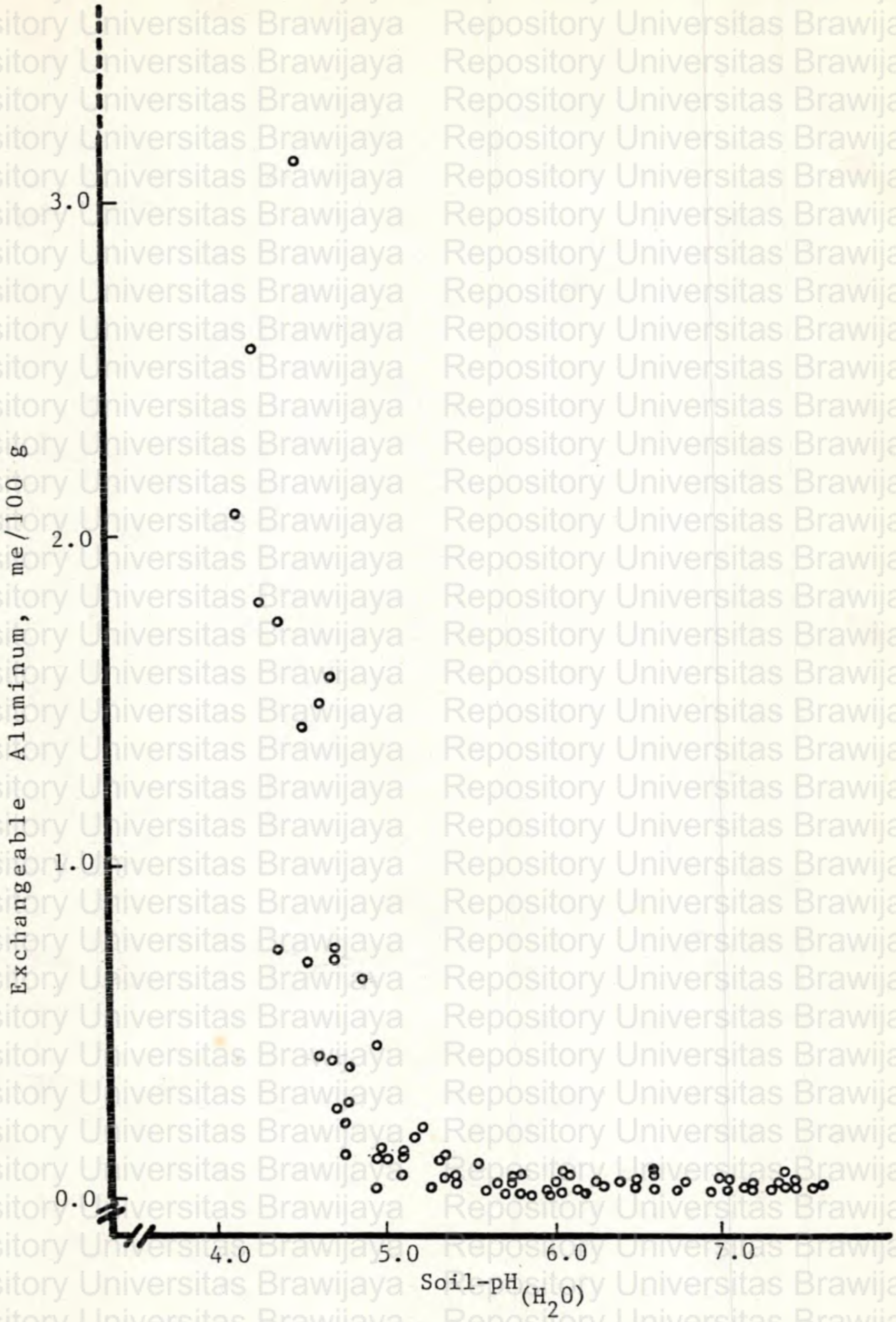

Figure 4. The Relationship between Soil-pH and Exchangeable Aluminum

occurs is in line with the evidence reported by many workers (Coleman et al, 1959; Moschler, Jones, and Thomas, 1960; Ayres, Hagihara, and Stanford, 1965; McLeod and Jackson, 1967; Pionke and Corey, 1967).

Effective Cation Exchange Capacity (ECEC)

As was shown previously, the permanent charge acidity or titratable acidity, and to some extent the pH-dependent charge acidity, were neutralized by $CaCO_3$ application. This neutralization resulted in an increase in net negative exchange sites. Thus, the cation exchange capacity of the soils increases accordingly. The magnitude of the increase depends on the buffering capacity. The CEC will supply information about the cation adsorption potentials of a soil. But, a more realistic approach is to measure the effective cation exchange capacity (ECEC). The ECEC of the soils in reponse to $CaCO_3$ increments is tabulated in Appendix Table 2 column 12. Twinty-one of the soils show an increase in ECEC with $CaCO_3$ increments. The rest of the soils (code numbers 4, 7, 11, 12, 26, 27, 28) did not follow this increasing trend. These seven soils, which have exch-Al^{+3} between 11.30 to 28.82 me Al^{+3} per 100 g soil, show a reduction in ECEC with the first 2-3 increments of $CaCO_3$, and a drastic increase with further $CaCO_3$ increments. This condition could be due to precipitation of the newly formed hydroxy-Al-polymers in interlayer position of 2:1 type minerals (Barnhisel and Rich, 1963; Hsu and Bates, 1964), and the increase with further $CaCO_3$ increments is associated with the formation of gibbsite.

Aluminum Saturation (Al-saturation)

The method used to calculate Al-saturation of the soils was the one used by Sanchez (1976 p 224). The calculated values are tabulated in Appendix Table 2 column 14. The relationship between Al-saturation and soil-$pH_{(H_2O)}$ as affected by $CaCO_3$ increments is presented in Figure 5. The curvilinear characteristics of the relationship has been previously reported by many workers (Abruna et al, 1975; Soares, Labato, Gonzalez, and Naderman, Jr., 1975; Sanchez, 1976; Fox, 1979). The Al-saturation and soil-pH relationships are more meaningful than the corresponding exch-Al^{+3} in describing the different rates of change of aluminum occupying the exchange sites at any soil-pH value in response to liming. Figure 5 shows that Al-saturation of the soils is drastically increased per unit decrease in soil-pH below $pH_{(H_2O)}$ 5.5; the higher the exch-Al^{+3} the higher is the Al-saturation value per unit pH drop below $pH_{(H_2O)}$ 5.5. Thus, its toxic potential will be much pronounced. On the contrary, when soil-$pH_{(H_2O)}$ reaches a value of 5.5 of higher the diffrences in Al-saturation approach a zero value; all of the soils have Al-saturation of less than 5 percent. At soil-$pH_{(H_2O)}$ 5.5 or higher, a minimum of 92.5 percent of aluminum neutralization is achieved (Figure 6).

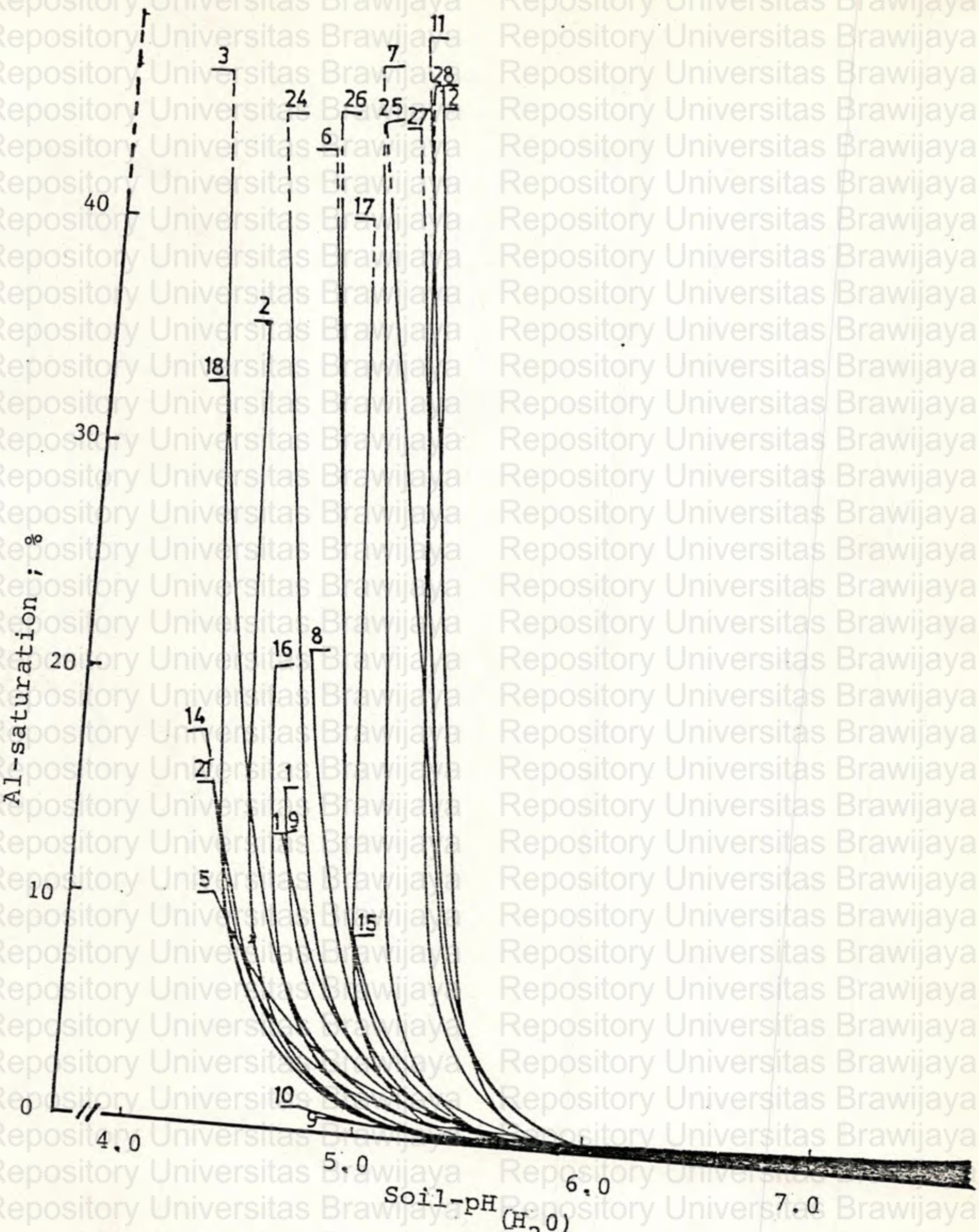

Figure 5. The Relationship Between Soil-pH $_{(H_2O)}$ and Aluminum Saturation

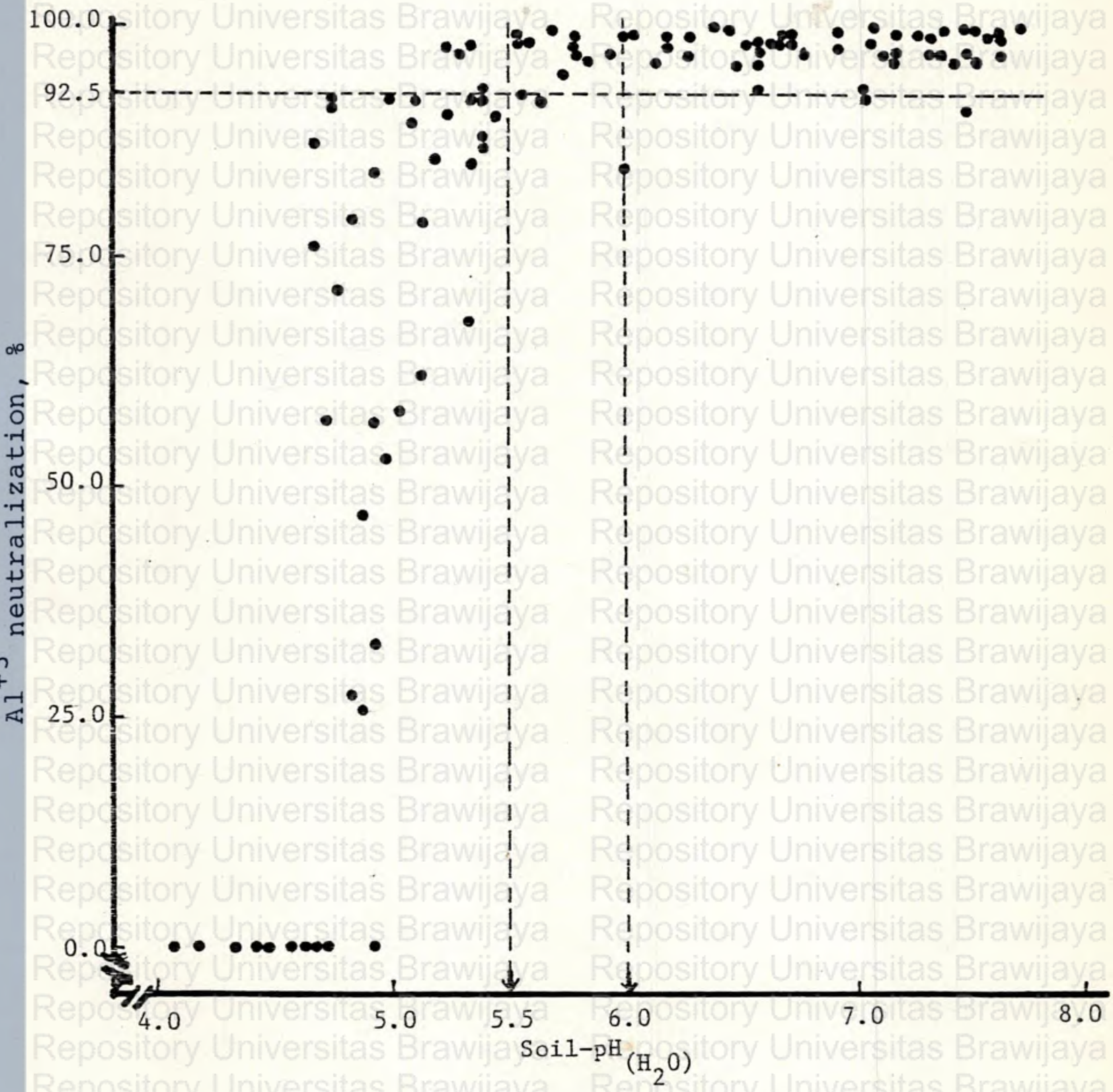

Figure 6. The Relationship between Soil-pH Aluminum Neutralization

Base Saturation (BS)

Base saturation of the soils as determined by NH_4OAc pH 7.0 extraction and titration with standard NaOH solution to the methyl-orange endpoint (BS_1) is tabulated in Appendix Table 2 column 16. Base saturation of the soils based on ECEC (BS_2) is tabulated in Appendix Table 2 column 15. The BS_1 increases linearly with increasing soil-pH as shown in Figure 7. The corresponding regression equation is:

$$BS_1\ (\%) = -\ 88.10 + 24.44\ pH_{(H_2O)} \quad (r = 0.933^{**}).$$

Base saturation calculated the basis of on ECEC exhibits different characteristics with soil-pH. The relationship with soil-pH is assymptotic (Figure 8). This kind of relationship was also reported by Pratt and Blair (1962) for several acid mineral soils in California. It is interesting to note, further, that this relationship is similar to the soil-pH-exchangeable-Al^{+3} relationship or to the soil-pH-Al-Saturation relationship, except that the last two relationships are negatively related to soil-pH. Figure 8 also indicates that the higher the exch-Al^{+3} content of the soil the faster is the rate of BS_2 reduction per unit pH drop from $pH_{(H_2O)}$ of 5.5, causing greater variation in BS_2 among the soils studied. At soil-$pH_{(H_2O)}$ 5.5, the soils have reached BS_2 values of about 82.5 percent, and at soil-$pH_{(H_2O)}$ 6.0 or higher, about 92.5 percent of the exchange sites is occupied by bases, mainly Ca^{+2} ions, because Ca^{+2} ions were the only element added in increasing amount.

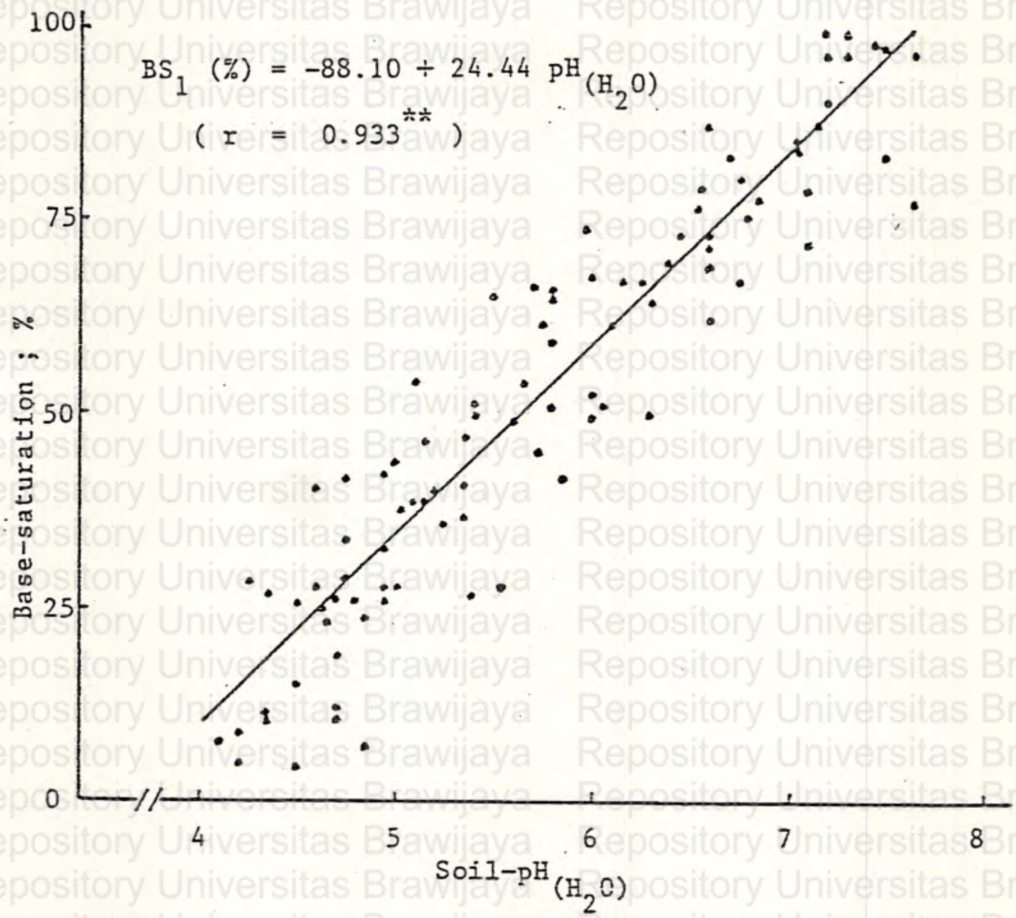

Figure 7. The Relationship between Soil-pH and Base Saturation Based on Cation Exchange Capacity

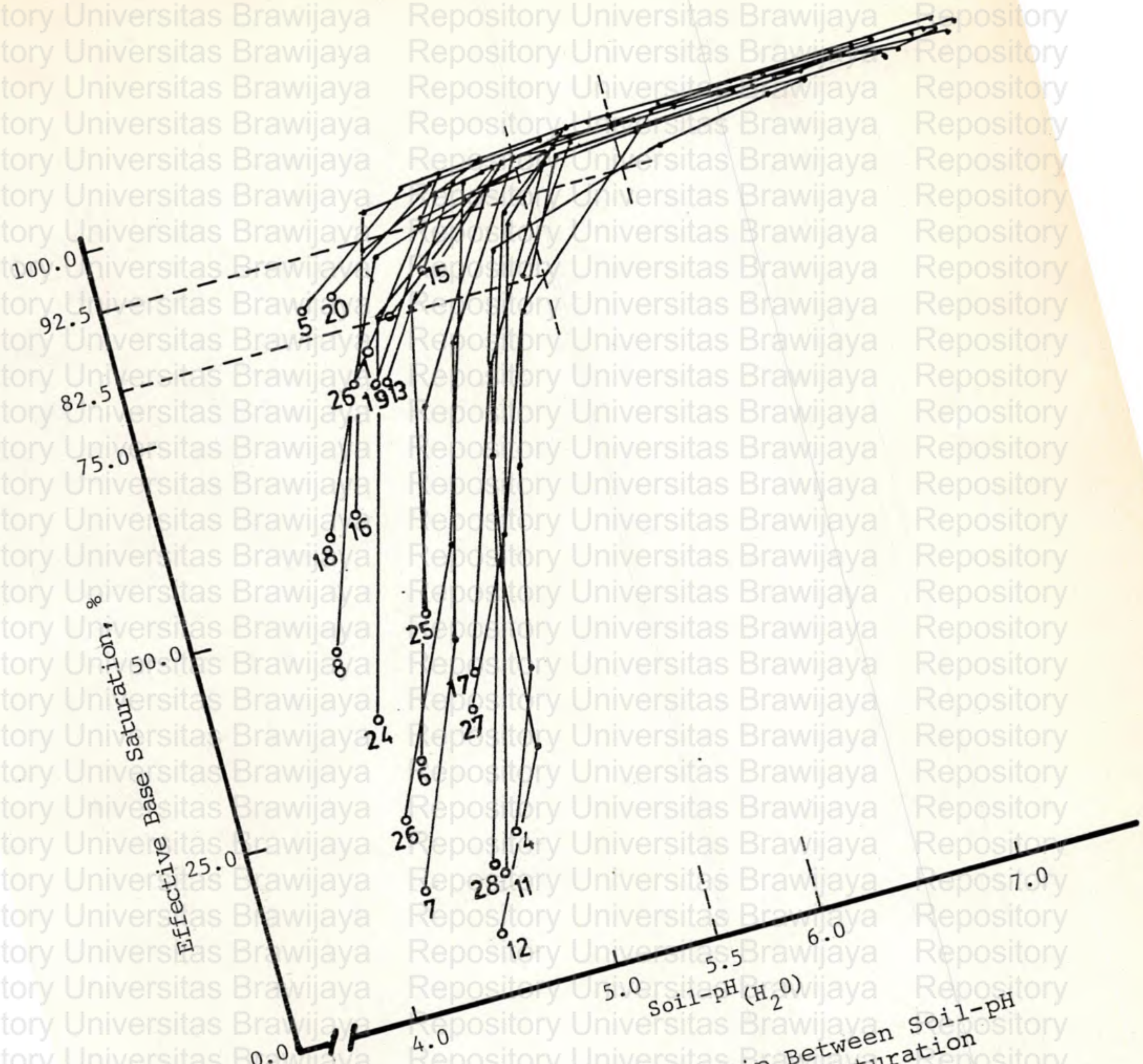

Figure 8. The Relationship Between Soil-pH and Effective Base Saturation

Calcium Carbonate or Calcium Hydroxide Equilibration

The use of $CaCO_3$ or $Ca(OH)_2$ determined LR test as the standard or reference LR test is quite common (McLean et al, 1960, 1966; Keeney and Corey, 1963; Ross et al, 1964; Yuan, 1974). It is derived by conducting an incubation experiment, and measuring pH changes with $CaCO_3$ or $Ca(OH)_2$ increments. The results are then plotted as scatter diagrams. This scatter diagram is known as the buffering curve. Some of the buffering curves of the soils studied, determined after 30 days incubation period, are presented in Figure 2.

The buffering curve is a reflection of composite contribution of all sources of acidity participating in the process within a particular pH range. Thus, the determined LR at any pH value takes into account the contribution of sources of acidity operating at and below the desired pH value.

The length of incubation period used by workers in the derivation of the reference LR test varies considerably. The shortest incubation period encountered was 30 days used by Reeve and Sumner (1970), and four weeks used by Kamprath (1970) when he developed the exch-Al^{+3} as a criterion for liming leached mineral soils. The longest period reviewed was 17 months by Ross et al (1964). The basic concept

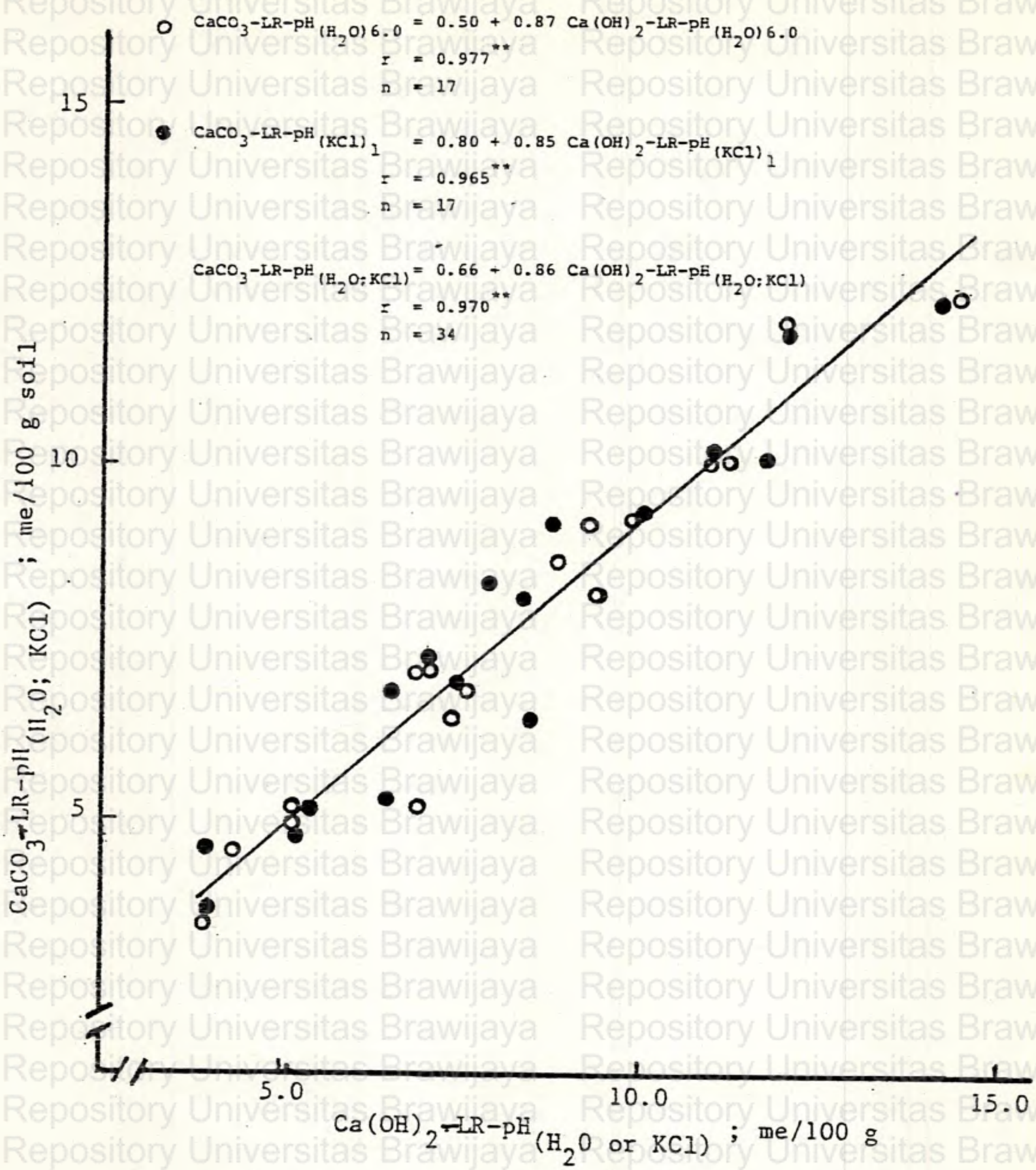

Figure 9. The Relationship between $CaCO_3$-LR Test and $Ca(OH)_2$-LR Test of the Soils

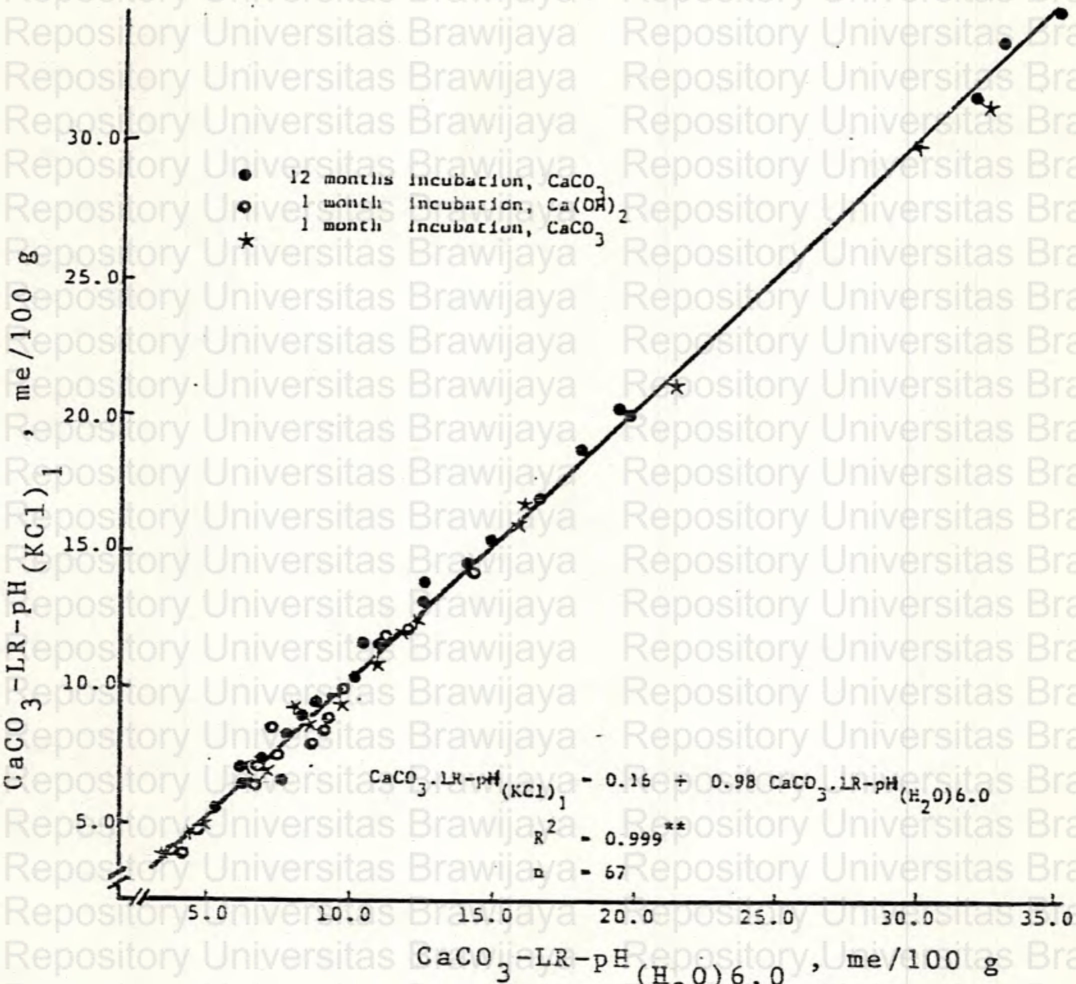

Figure 10. The Relationship between $CaCO_3$-LR-pH$_{(H_2O)6.0}$ and Its Corresponding $CaCO_3$-LR-pH$_{(KCl)1}$

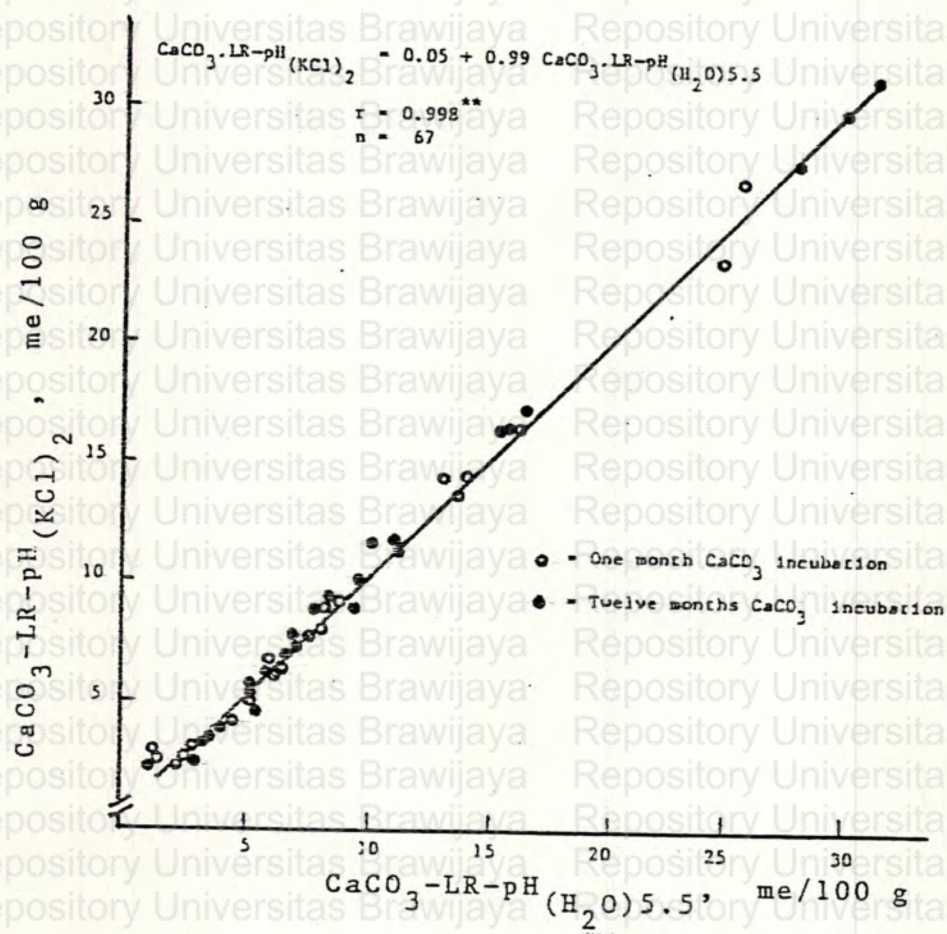

Figure 11. The Relationship between $CaCO_3$-LR-pH$_{(H_2O)5.5}$ and Its Corresponding $CaCO_3$-LR-pH$_{(KCl)2}$

incubation period of 30 days (Appendix Table 6 columns 5, 7, 9, and 11). This indicates that additional 11 months incubation period caused a pH reduction. Sources of acidity responsible for the increase in acidity or to the increase in LR, are classified as pH-de½endent acidity sources, where H^+ ions are released from deprotonation of hydroxy-Al and hydroxy-Fe species, and from hydrogen covalently bonded to organic matter (Pionke and Corey, 1967). The other contribution is from ionic strength build-up due to mineralization of organic matter, and production of NO_3^- - N and sulphate ions. The effect of ionic strength or salt concentration on pH has been discussed extensively by Van Raij and Peech (1971), Morais et al (1976), and Sanchez (1976, p.135-161). The parallelism test conducted in relation to this matter was not significant at the 5 percent probability level. Therefore, the rate of pH drop or the increase in lime requirement of the soils samples incubated for 12 months are relatively the same for all soils used in this experiment.

The Buffer Lime Requirement Tests

The SMP-LR-$pH_{6.0}$ test values are presented in Appendix Table 6 column 12. The average value of the 28 soils was 12.74 me $CaCO_3$ per 100 g soil, with the minimum-maximum range value of 4.80-26.60 me $CaCO_3$ per 100 g soil. The SMP-LR-$pH_{6.0}$ test values are higher than the reference LR test values, except for soil code numbers 11 and 12 (Podzolic Gajruk). The tendency for the SMP-LR-$pH_{6.0}$ test to produce higher values than the reference LR test values was also observed by several workers (Keeney and Corey, 1963; Ross et al, 1964). This may be because the SMP-LR test recommendations are more suited for field conditions rather than to laboratory conditions (Ross et al, 1964). The underestimated values for Pozolic soil from Gajruk (exch-Al^{+3} > 20 me Al^{+3} per 100 g soil) should be interpreted as being beyond the capacity of the buffer solution. The derived values were obtained by extrapolation below the linear range of the original data presented by Shoemaker et al (1961)

The relationships of the SMP-LR-$pH_{6.0}$ with the reference LR tests are presented in Table 9 and in Figure 12-13.

Table 9. Relationship between the SMP-LR-$pH_{6.0}$ and the $CaCO_3$-Determined LR Tests

Soil group	The Reference LR test (Y_i)	Regression equation	r-value
A (n=13)	$CaCO_3$-LR-$pH_{(H_2O)6.0}$	$Y = -0.47 + 0.90\ X^{a/}$	0.974^{**}
B (n=11)	-"-	$Y = -4.30 + 1.52\ X$	0.892^{**}
A+B (n=24)	-"-	$Y = -1.91 + 1.04\ X$	0.937^{**}
A (n=13)	$CaCO_3$-LR-$pH_{(H_2O)5.5}$	$Y = -1.34 + 0.71\ X$	0.960^{**}
B (n=11)	-"-	$Y = -4.58 + 0.98\ X$	0.914^{**}
A+B (n=24)	-"-	$Y = -3.09 + 0.91\ X$	0.953^{**}

a/ X = The SMP-LR-$pH_{6.0}$ test value. Both LR tests were calcultaed on the basis of me/100 g soil

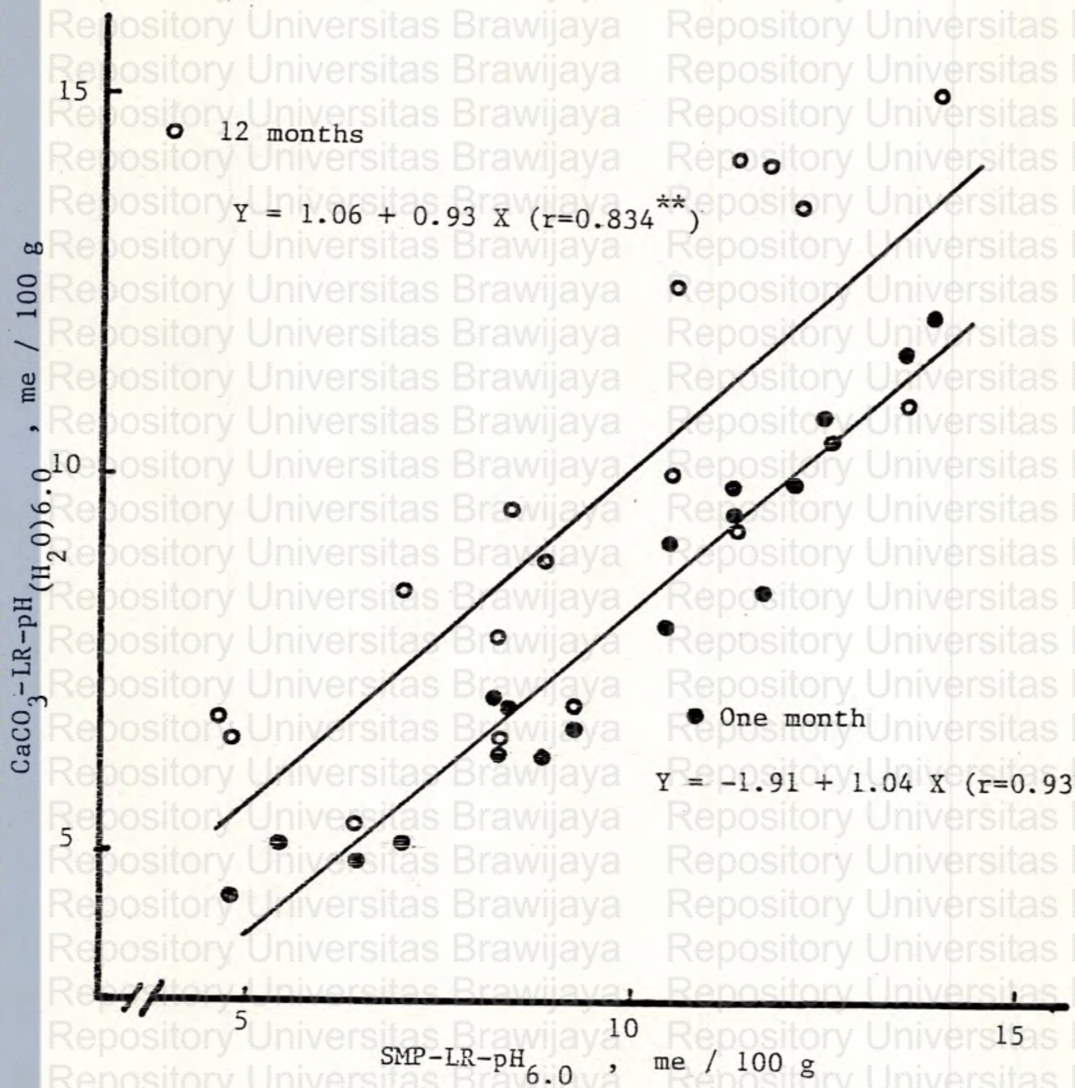

Figure 12. The Relationship Between SMP-LR-$pH_{6.0}$ and $CaCO_3$-LR-$pH_{(H_2O)6.0}$

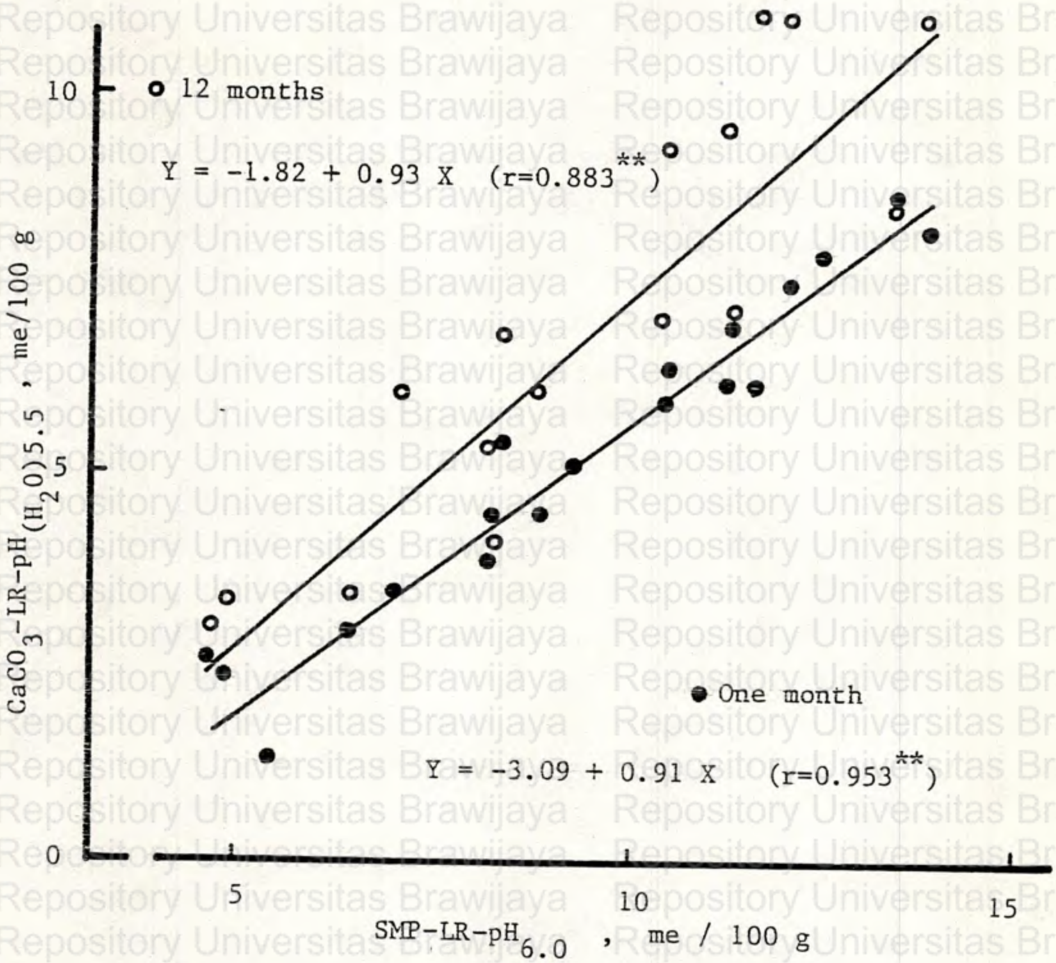

Figure 13. The Relationship Between SMP-LR-pH$_{6.0}$ and $CaCO_3$-LR-pH$_{(H_2O)5.5}$

The relationships with the corresponding $CaCO_3$-LR-$pH_{(KCl)1}$ or $CaCO_3$-LR-$pH_{(KCl)2}$ are presented in Figures 14 and 15. The SMP-LR-$pH_{6.0}$ correlates very closely to the reference lime requirement tests. Better correlation coefficients were exhibited with the acid soils in group A than with the acid soils in group B (Table 9). The tendency of the SMP-LR test value to correlate better with the reference lime requirement test value of acid mineral soils, where sources of acidity are mainly pH-dependent sources, was also reported by Corey et al (1971).

The relationship of the SMP-LR-$pH_{6.0}$ to the $CaCO_3$-LR tests with 30 days incubation was better than that with the $CaCO_3$-LR tests using 12 months incubation (Figures 12 to 15), indicating that the LR using 30 days incubation with $CaCO_3$ is better for testing the reliability of the SMP Buffer-LR method. The overall conclusion is that if other LR tests require laborous steps in the routine soil testing framework, the SMP-LR-$pH_{6.0}$ would appear to be the logical choice for a LR test, especially for acid mineral soils where sources of acidity are mainly pH-dependent.

The SMP-DB-LR-pH(H_2O) test was among the buffer methods studied. The derived SMP-DB-LR-$pH_{6.0}$ values, together with the corresponding $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and the SMP-LR-$pH_{6.0}$, are presented in Table 10. The SMP-DB-LR-$pH_{6.0}$ test values of the soils with code numbers 11, 12, 22, 26, 27, and 28

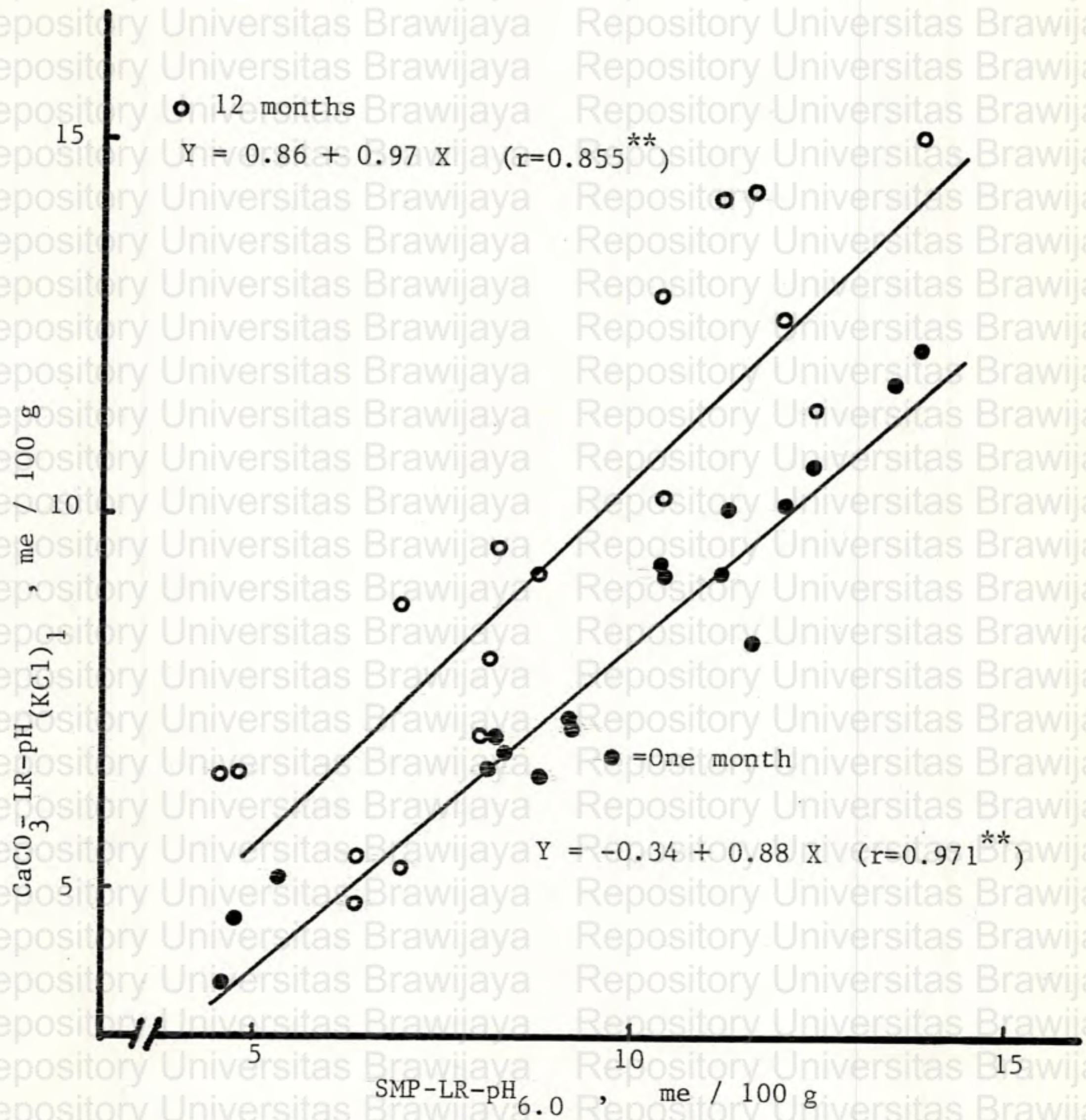

Figure 14. The Relationship Between SMP-LR-$pH_{6.0}$ and $CaCO_3$-LR-$pH_{(KCl)1}$

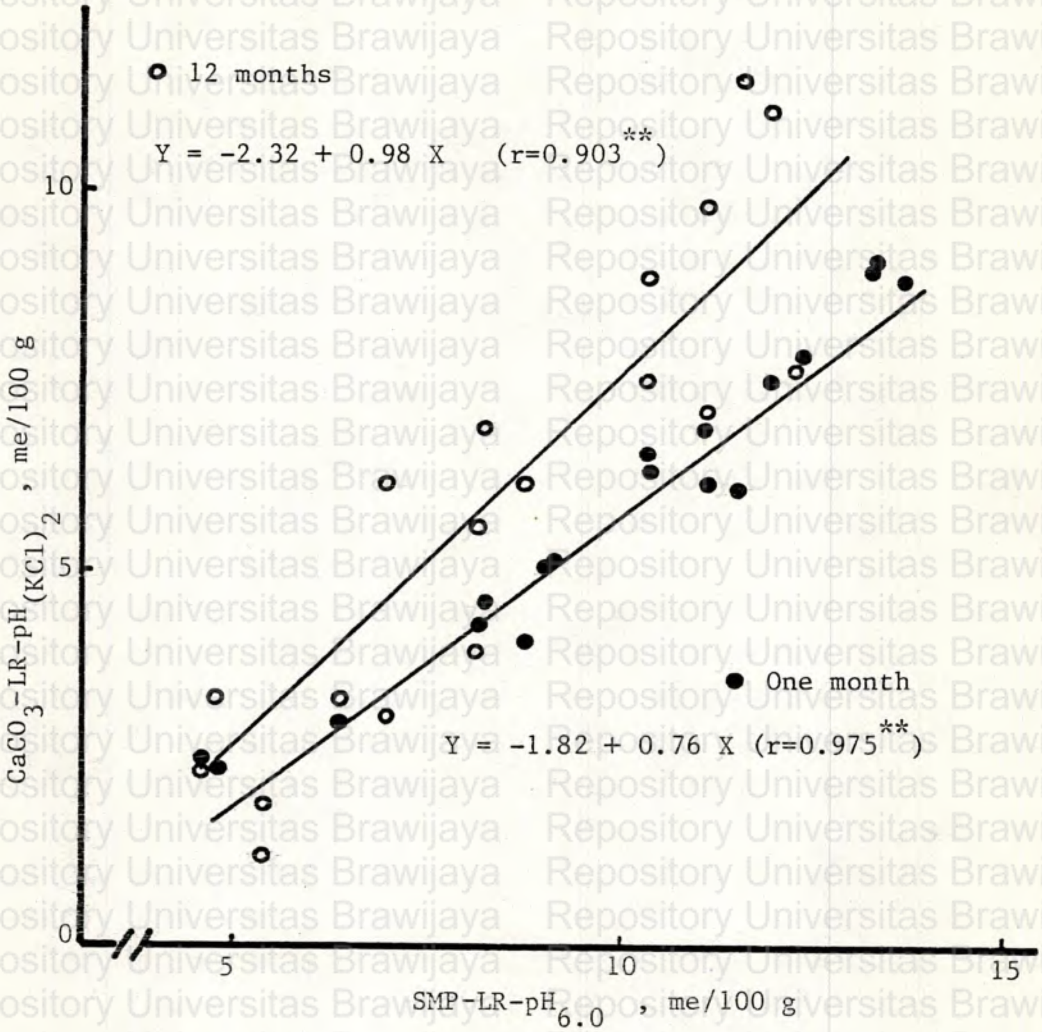

Figure 15. The Relationship Between SMP-LR-$pH_{6.0}$ and $CaCO_3$-LR-$pH_{(KCl)2}$

were negative, and the reason of this discrepancy is not understood. It could be that the SMP-DB-LR test is basically for estimating low LR of acid mineral soils (McLean, et al, 1978), while these particular acid soils are high in exch-Al^{+3} (Appendix Table 1 column 17), and their LRs are very high. When the calculated SMP-DB-LR-$pH_{6.0}$ test values are related to the corresponding $CaCO_3$-LR-$pH_{6.0}$, a highly significant correlation coefficient is obtained ($r = 0.830^{**}$; Table 10). The regression equation is:

$$CaCO_3\text{-LR-pH}_{(H_2O)6.0} = 2.48 + 0.78\ \text{SMP-DB-LR-pH}_{6.0} \quad (r = 0.830^{**})$$

But, when the correlation coefficient is compared to the corresponding correlation coefficient of the SMP-LR-$pH_{6.0}$ with the same reference LR test, as shown by the regression equation:

$$CaCO_3\text{-LR-pH}_{(H_2O)6.0} = -\ 0.50 + 0.89\ \text{SMP-LR-pH}_{6.0} \quad (r = 0.973^{**})$$

the SMP-DB-LR-$pH_{6.0}$ is obviously less suitable for predicting LR of the acid mineral soils as a group.

The Yuan-DB-LR-$pH_{6.0}$ also gave a lower correlation coefficient with the $CaCO_3$-LR-$pH_{(H_2O)}$; it could only explain about 53 percent of the variability of the dependent variable.

The SMP-DB-LR test and Yuan-DB-LR test require laborous laboratory work and calculations. Therefore, it is best not to use them for determining LR of the soils, unless additional research work will prove they are reliable for acid soils low in lime requirement.

Table 10. The SMP-DB-LR-$pH_{6.0}$, $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and the SMP-LR-$pH_{6.0}$ Test Values

Soil code number	SMP DB LR-$pH_{6.0}$	$CaCO_3$ LR-$pH_{(H_2O)6.0}$	SMP LR-$pH_{6.0}$
	....	(me $CaCO_3$/100 g)	....
1	6.49	7.15	8.20
2	5.03	6.85	9.20
3	7.59	11.92	13.40
5	11.54	9.25	10.40
8	9.53	10.05	11.20
9	2.44	4.50	4.80
10	5.84	7.10	8.30
11	- a/	30.05	25.80
12	-	32.55	26.60
13	3.97	4.95	6.40
14	5.33	5.20	5.40
15	4.48	5.20	7.00
16	7.17	8.65	11.60
17	4.45	3.50	4.60
18	8.73	10.05	12.00
19	6.04	8.20	10.40
20	5.01	6.45	8.80
21	13.88	12.35	13.80
22	-	16.70	21.50
23	6.91	6.50	8.20
24	8.27	11.00	12.40
25	8.59	9.70	11.20
26	-	15.95	22.00
27	-	16.15	23.20
28	-	21.45	22.00

a/ The "d-value" calculated with the original equation given by McLean *et al* (1978) was negative. Therefore, the LR test value could not be derived.

Lime Estimation Based on Soil Properties

The selected soil properties possibly affecting the LR of the soils were assumed to be: pH, percent OM, percent clay, TAc, exch-Ac, exch-Al^{+3}, nonexch-Al, and ECEC. These soil properties, except ECEC, had been studied by Keeney and Corey (1963), and by Roos et al (1964) for Wisconsin and Michigan acid mineral soils, respectively. In the case of acid mineral soils in the tropics exch-Al^{+3} has received the greatest attention in determining LR (Kamprath, 1970, 1972; Corey et al, 1971; Reeve and Sumner, 1971).

The selected soil properties are presented in Appendix Table 1. The reference LR tests are listed in Appendix Table 6. Simple correlation analyses were carried out to determine which of the soil properties were important enough to be considered in further statistical analyses. The results are presented in Table 11. Further discussion is based on each soil group.

Soil Group A. Among the soil properties, percent clay has the poorest relationship with the reference LR tests, followed by soil-pH, nonexch-Al, and ECEC. The four correlation coefficients were not significant at the 5 percent probability level. The TAc was significantly related to the $CaCO_3$-LR-$pH_{(H_2O)5.5}$ ($r = 0.614^*$), but not to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$. The same relationship was observed with the exch-Al^{+3}. The reverse situation was observed with exch-Ac

Table 11. Simple Correlation Coefficients Among The Soil Properties with The Reference LR Tests

Reference LR Test	Soil parameter	Correlation coefficient $A^{a/}$ (n=13)	$B^{a/}$ (n=11)	$A + B^{a/}$ (n=24)
$CaCO_3$-LR-$pH_{(H_2O)}$6.0	$pH_{(H_2O)}$	-0.145	-0.110	-0.514*
	% OM	0.790**	0.231	0.229
	% Clay	-0.109	0.274	-0.134
	TAc	0.512	0.969**	0.959**
	Exch-Ac	0.714**	0.956**	0.931**
	Exch-Al^{+3}	0.518	0.974**	0.960**
	Nonexch-Al	0.261	0.482	0.503*
	ECEC	-0.151	0.965**	0.692**
$CaCO_3$-LR-$pH_{(H_2O)}$5.5	$pH_{(H_2O)}$	-0.387	-0.139	-0.572*
	% OM	0.7 **	0.219	0.194
	% Clay	0.029	0.259	-0.127
	TAc	0.614*	0.973**	0.965**
	Exch-Ac	0.534	0.946**	0.905**
	Exch-Al^{+3}	0.584*	0.971**	0.959**
	Nonexch-Al	0.029	0.473	0.414*
	ECEC	-0.111	0.968**	0.694**

a/ Group A = Soils with exch-Al^{+3} < 1.97 me Al^{+3}/100 g
B = Soils with exch-Al^{+3} between 1.99 to 28.82 me/100 g
A+B = Soils with exch-Al^{+3} between 0.06 to 28.82 me/100 g

where its relation to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ was significant ($r = 0.714^{**}$), but not to the $CaCO_3$-LR-$pH_{(H_2O)5.5}$. The greatest contributor to acidity as measured by reference LR tests was percentage of organic matter ($r = 0.790^{**}$ and $0.0.714^{**}$; Table 11 column 3).

Soil Group B. Among the soil properties contributing to LR, exch-Al^{+3}, TAc, exch-Ac, and ECEC were highly related to the reference LR tests. The correlation coefficients were about the same magnitude (Table 11 column 4). The most significant change in contribution to LR of the soils in this group when compared to group A was that percentage organic matter, which proved to be very important contributor in group A, was not important for soils in group B. The contributions of percent clay, pH, and nonexch-Al were insignificant in this group.

Soil Group A+B. The soil properties contributing to lime requirement of the soils in this group were the same as those observed in group B, indicating that the inclusion of acid mineral soils having exch-Al^{+3} less than 1.97 me Al^{+3} per 100 g soil or Al-saturation less than 30 percent did not have any effect on the regression analysis. This implies that the grouping of the 28 soils into two group is justified. The highly significant correlation coefficients obtained between ECEC and $CaCO_3$-determined LR tests for soils in group B and group A+B was indicated by the highly significant effect of TAc, exch-Ac, and exch-Al^{+3} on ECEC (Appendix Table 7). Therefore, a highly significant relationship between ECEC and the reference LR tests should be expected. At a given pH value the ECEC is related to reserve acidity and because the major portion of lime reacts with reserve acidity, LR increases with increasing in potential acidity.

Though simple correlation coefficients were used to indicate which soil properties may be important in determining LR, they may not accurately predict contributions of each soil property to LR of acid mineral soils because of interactions or colinearities among soil properties (Appendix Table 7). Therefore, the relative importance of each soil property in predicting LR is better evaluated by multiple regression analyses. The multiple regression used in this study was the forward selection procedure given by Kleinbaum and Kupper (1978, section 15.2.3).

In the following discussion, the stadardized partial regression coefficients (β_i') were used to compare the relative contribution of each soil property to the LR of the acid mineral soils. the level of significance of the dependent variable was evaluated from the corresponding partial F-ratio value. When the last independent variable entered in the regression equation has a partial F-ratio value which was not significant at the 10 percent probability level, the process of computation was terminated. When the stadardized partial regression coefficient of one independent variable was twice that of another independent variable within the same multiple regression equation, then that variable was twice as important as the other one in predicting the dependent variable (Steel and Torrie, 1960, p 284). These comparison are made in Table 12 and 13. The dependent variables were the reference LR test values. The results are as follows:

Soil Group A. The percentage of OM is the most important soil property contributing to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and to the $CaCO_3$-LR-$pH_{(H_2O)5.5}$. Its partial F-ratio values were significant at the one percent ptobability level. Exchangeable acidity and nonexch-Al contribution to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and the contribution of exch-Ac to the $CaCO_3$-LR-$pH_{(H_2O)5.5}$ were significant at the 5 percent probability level. The relative importance of the percentage OM compared to the other soil properties was one and a half times to twice as important as exch-Ac or exch-Al^{+3}. The overall results showed that soil properties contributing to LR of the soils, when liming to achieve a soil-$pH_{(H_2O)}$ of 6.0 or 5.5, are those properties exhibiting pH-dependent acid characteristics. The exch-Al^{+3} does not give a significant contribution to lime requirement of 13 acid mineral soils in this group. Sixty-nine percent of the soils have exch-Al^{+3} of less than 1.0 me Al^{+3} per 100 g soil and the average Al-saturation was

Table 12. Multiple Regression Analyses by Forwards Selection Procedure of The Soil Properties Contributing to Lime Requirement

group	LR test	Regression F-value	Determ. (R^2;%)	Soil parameter (X_i)	Regr. coeff. (β_i)	Std. Error of Regr. coeff. (S_{β_i})	Std. coeff. of regr. (β'_i)	Partial F-value ($\beta_i^2/S_{\beta i}^2$)
A (n=13)	$CaCO_3$-LR-$pH_{(H_2O)}$ 6.0	12.311**	86.0	X_0=constant	-1.3925	-	-	-
				X_2= % OM	2.4575	0.5690	0.731	18.654**
				X_5=Exch-Ac	0.6907	0.2190	0.537	9.947*
				X_7=Nonexch-Al	-0.4122	0.1559	- 0.502	6.991*
				X_8= ECEC	-0.0625	0.0497	- 0.199	1.597 n.s.
B (n=11)	$CaCO_3$-LR-$pH_{(H_2O)}$ 6.0	105.704**	96.4	X_0=constant	4.4031	-	-	-
				X_6=Exch-Al^{+3}	0.8058	0.0636	0.925	160.524**
				X_7=Nonexch-Al	0.4432	0.2517	0.129	3.101 n.s.
A+B	$CaCO_3$-LR-$pH_{(H_2O)}$ 6.0	119.967**	96.6	X_0=constant	0.5827	-	-	-
				X_6=Exch-Al^{+3}	0.6747	0.1229	0.718	30.138**
				X_5=Exch-Ac	0.4995	0.2625	0.257	3.621 a/
				X_2= % OM	0.8697	0.6042	0.082	2.072 n.s.

**, *, a/ = Significant at the one, 5, and 10 percent probability level, respectively
n.s = Nonsignificant at the 5 percent probability level

Table 13. Multiple Regression Analyses by Forwards Selection Procedure of The Soil Properties Contributing to Lime Requirement

Soil group	The Reference LR test	Overall Regression F-value	Coeff. Determ. (R^2;%)	Soil parameter (X_i)	Regr. Coeff. (β_i)	Std.Error of Regr.Coeff. (S_{β_i})	Std.coeff. of Regr. (β_i)	Partial F-value ($\beta_i^2/S_{\beta_i}^2$)
A (n=13)	$CaCO_3$-LR-$pH_{(H_2O)}5.5$	10.602**	88.3	X_0=constant	18.9482	-	-	-
				X_2= % OM	2.5091	0.7606	0.932	10.881**
				X_7= ECEC	- 0.3847	0.1070	- 0.585	11.920**
				X_5=Exch-Ac	0.4766	0.1764	0.463	7.300*
				X_1= pH	- 4.1922	1.7904	- 0.556	5.483*
				X_4= T-Ac	- 1.2677	1.1868	- 0.348	1.141 n.s.
B (n=11)	$CaCO_3$-LR-$pH_{(H_2O)}5.5$	65.964**	96.6	X_0=constant	-19.2440	-	-	-
				X_4= T-Ac	0.6820	0.0498	0.996	187.547**
				X_1= pH	5.1306	2.6478	0.159	3.755 a/
				X_2= % OM	0.7920	0.7843	0.082	1.020 n.s.
A+B	$CaCO_3$-LR-$pH_{(H_2O)}5.5$	161.630**	93.9	X_0=constant	2.4797	-	-	-
				X_4= T-Ac	0.7040	0.0400	0.958	309.760**
				X_2= % OM	0.8264	0.4952	0.090	2.785 n.s.

**, *, a/ = Significant at the one, 5, and 10 percent probability level, respectively
n.s = Nonsignificant at the 5 percent probability level

15.2 percent or about 25 percent below the critical level for Al-toxicity in corn or about 5 percent below that for soybean (Kamprath, 1970). The 15.2 percent Al-saturation value is close to the value reported by Kamprath (1970) when acid mineral soils were limed based on 1.5 times the exch-Al^{+3}. There is substantial evidence in the literature that there should be no potential danger of Al-toxicity for growing crops on these soils, and that LR based on 1.5 times exchangeable aluminum will underestimate the actual LR. Assuming that pH adjustment as proposed by McLean (1971) will increase their ECEC, the best fit regression equations to assess LR of the soils are as follows:

$$\text{LR-pH}_{(H_2O)6.0} = -2.34 + 2.29\ (\%\text{OM}) + 0.71\ \text{exch-Ac} - 0.31\ \text{nonexch-Al}$$
$$(R^2 = 0.832^{**})$$

$$\text{LR-pH}_{(H_2O)5.5} = 10.81 + 1.85\ (\%\text{OM}) - 0.37\ \text{ECEC} + 0.52\ \text{exch-Ac} - 2.60\ \text{pH}_{(H_2O)}$$
$$(R^2 = 0.864^{**})$$

But, because of their R^2 values are lower than the R^2 value of the SMP-LR tests (Table 9), the two derived multiple regression equations are less favored than the SMP-LR test.

<u>Soil Group B</u>. A completely different picture was shown by the soil properties contributing to LR of the soils in group B. In this group, exch-Al^{+3} appears to be the dominant contributor to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$, and the TAc is the dominant contributor to the $CaCO_3$-LR-$pH_{(H_2O)5.5}$.

The TAc which is highly related to the exch-Al^{+3} of this group ($r = 0.989^{**}$; Appendix Table 7 column 8 and 11), indicating that the exch-Al^{+3} indeed plays the greatest role in determining LR of the acid mineral soils having an average Al-saturation of 60 percent. Ninety-five percent of the variability of the reference LR test values could be explained by exch-Al^{+3}. The corresponding SMP-LR-$pH_{6.0}$ has correlation coefficient 0f 0.892^{**} and 0.914^{**} with the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and $CaCO_3$-LR-$pH_{(H_2O)5.5}$, respectively (Table 9), or 15 and 12 percent less, respectively, in explaining the variability of the reference LR test values. The best fit regression equations are:

$$CaCO_3\text{-LR-}pH_{(H_2O)6.0} = 7.53 + 0.85 \text{ exch-}Al^{+3} \quad (r = 0.974^{**})$$

$$CaCO_3\text{-LR-}pH_{(H_2O)5.5} = 4.96 + 0.67 \text{ TAc} \quad (r = 0.973^{**})$$

or: $$CaCO_3\text{-LR-}pH_{(H\ O)5.5} = 5.71 + 0.70 \text{ exch-}Al^{+3} \quad (r = 0.971^{**})$$

<u>Soil Group A+B</u>. The soil properties contributing to LR of the 24 soils in this group were the same as those in group B (Table 12, and 13, column 5). Exchangeable-Al^{+3} and TAc are the dominant contributors to the reference LR tests. The inclusion of the soils from group A in the multiple regression analyses resulted in a slight reduction in the coefficients of determination.

Another measure to evaluate the contribution of exchangeable-Al^{+3} to LR of the acid mineral soils is by

Table 14. Contribution of Exchangeable aluminum to Lime Requirement of The Soils Studied

Soil	Exch–Al^{+3}	$CaCO_3$-LR-$pH_{(H_2O)}$ 5.5	$CaCO_3$-LR-$pH_{(H_2O)}$ 6.0	$\left(\frac{Exch-Al^{+3}}{CaCO_3-LR-pH_{5.5}}\right)$	$\left(\frac{Exch-Al^{+3}}{CaCO_3-LR-pH_{6.0}}\right)$
	.... (me/100 g)			.... (ratio)	
A: 14	0.06	1.30	5.20	0.016	0.012
9	0.15	2.40	4.50	0.062	0.033
10	0.41	5.50	7.10	0.075	0.058
23	0.48	4.00	6.50	0.120	0.074
5	0.60	6.50	9.25	0.092	0.065
13	0.70	3.00	4.95	0.233	0.141
20	0.83	4.55	6.45	0.182	0.129
1	0.89	4.55	7.15	0.196	0.124
15	0.92	3.50	5.20	0.263	0.177
17	1.17	2.65	3.50	0.442	0.334
21	1.28	8.40	12.35	0.152	0.104
19	1.37	6.05	8.20	0.226	0.267
8	1.97	6.35	10.05	0.310	0.196
B: 3	1.99	8.85	11.92	0.225	0.167
2	2.18	5.30	6.85	0.411	0.356
24	2.55	8.05	11.00	0.317	0.232
25	2.96	7.15	9.70	0.414	0.305
18	3.18	7.70	10.05	0.413	0.316
22	8.09	14.15	16.70	0.572	0.484
26	11.96	13.70	15.95	0.873	0.750
27	12.51	13.20	16.15	0.948	0.778
28	18.66	16.35	21.45	1.141	0.870
11	24.33	25.00	30.05	0.973	0.810
12	28.82	25.75	32.55	1.119	0.885

deviding the exch-Al^{+3} value of each soil by the corresponding $CaCO_3$-LR-$pH_{(H_2O)6.0}$ or 5.5 and multiplying it by a factor of 100. The calculated results are presented in Table 14. For soils in group A, the contribution of exch-Al^{+3} to the $CaCO_3$-LR-$pH_{(H_2O)6.0}$ and $CaCO_3$-LR-$pH_{(H_2O)5.5}$ were only 18.2 and 12.4 percent, respectively. On the contrary, the contribution of exch-Al^{+3} of the soils in group B to the same reference LR tests were 67.3 and 54.1 percent, repectively. These results confirm and strengthen the results of the multiple regression analyses discussed previuosly.

Greenhouse Experiment-I

The Effect of $CaCO_3$ Application on Dry Matter Yield

Dry matter yields of experimental hybrid corn 17x16 in response to $CaCO_3$ application were tabulated in Appendix Table 8. Dry matter yields on the top-layer soils were higher than on the corresponding sub-layer soils over all $CaCO_3$ increments. The limed soils gave higher yields, and the increase were significant at the one percent probability level. Dry matter yield responses to the $CaCO_3$ levels used were curvilinear, only on BFS_{30-60} the response was linear over all $CaCO_3$ increments (Figure 16). Dry matter yield reduction at the 1.25 SMP-lR-$pH_{6.0}$ levels for G_{0-30}, Sitiung, and BFS_{0-30} were significant ($P_{0.05}$), but not significant on D_{0-30}, D_{30-60}, G_{30-60} and BFS_{30-60} (Table 15).

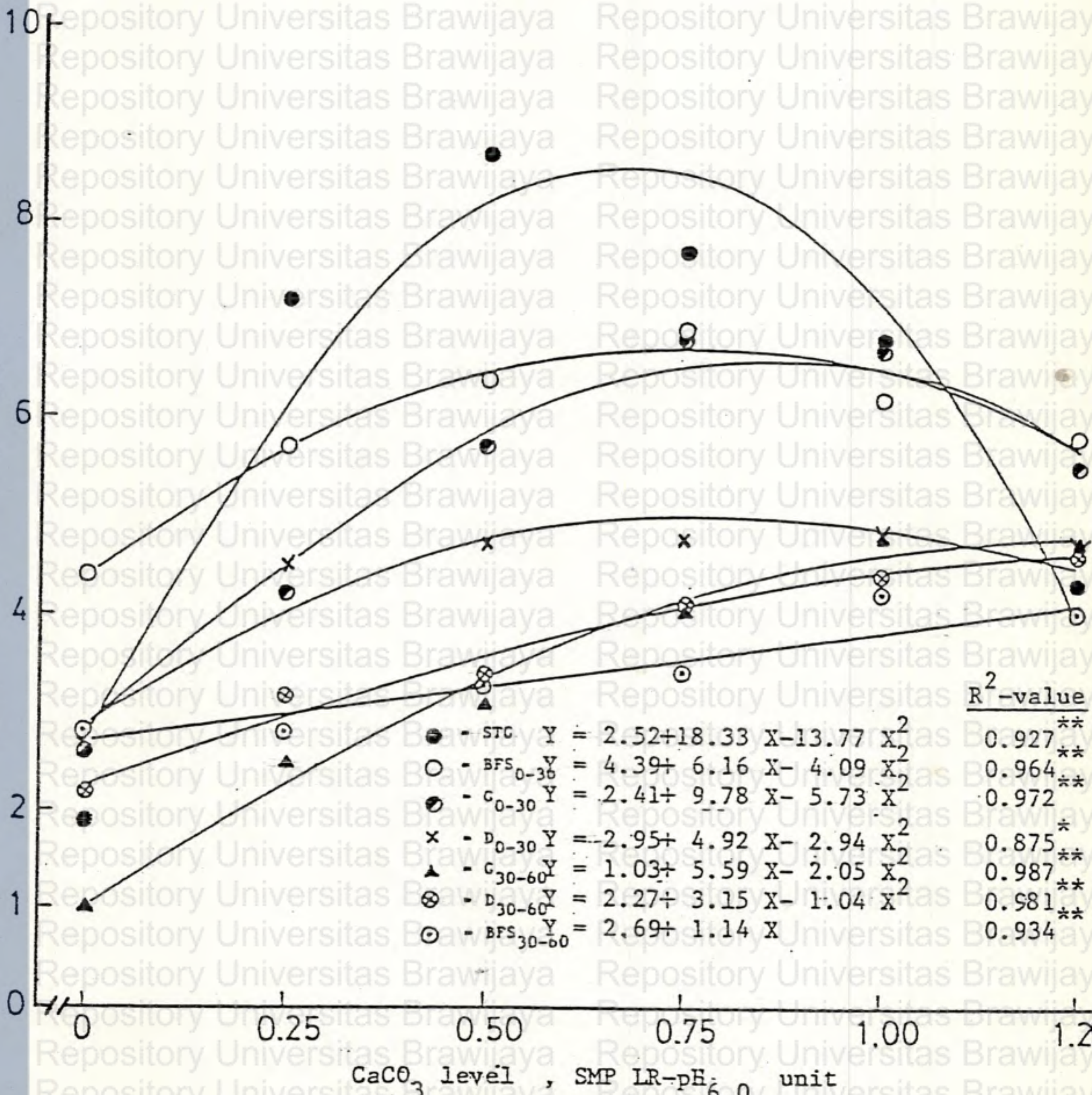

Figure 16. The Effect of Lime Application on Dry Matter Production of Corn

The largest yield response occured with lower levels of $CaCO_3$ application, and the maximum yields were obtained at higher $CaCO_3$ levels within the 0.50 to 1.00 SMP-LR-$pH_{6.0}$ unit range.

When dry matter yields were related to the corresponding soil-$pH_{(H_2O)}$ changes, the largest yield response was obtained when soil-$pH_{(H_2O)}$ was increased to 5.3, and the highest dry matter yields occured within soil-$pH_{(H_2O)}$ 5.5 to 6.0. Beyond soil-$pH_{(H_2O)}$ 6.0, dry matter yield decreased on the top-layer soils (Figure 17).

Table 15. Dry Matter Yields [a/] of Corn in Response to $CaCO_3$ Application

$CaCO_3$ appl.	Soil						
SMP-LR-$pH_{6.0}$ unit	D [b/] 0-30	D 30-60	STG	G 0-30	G 30-60	BFS 0-30	BFS 30-60
	(g/pot)						
0.00	2.68	2.20	1.93	2.64	1.00	4.36	2.83
0.25	4.48	3.19	7.17	4.17	2.46	5.70	2.78
0.50	4.72	3.14	8.66	5.68	3.09	6.41	3.30
0.75	4.75	4.07	7.70	6.76	4.02	6.90	3.40
1.00	4.77	4.40	6.80	6.70	4.79	6.17	4.16
1.25	4.69	4.58	4.13	5.48	4.71	5.80	3.98
L.S.D.$_{0.05}$	0.72	0.58	1.14	1.06	0.60	1.07	0.74

a/ Average of three replicates; the experimental hybrid corn plants were harvested at 35 days after planting, 72 hours at 60°C oven dried.

b/ D = Darmaga, STG = Sitiung, G = Gajruk, BFS = Brown Forest Soil; 0-30 or 30-60 = soil sampled from 0-30 or 30-60 cm depth

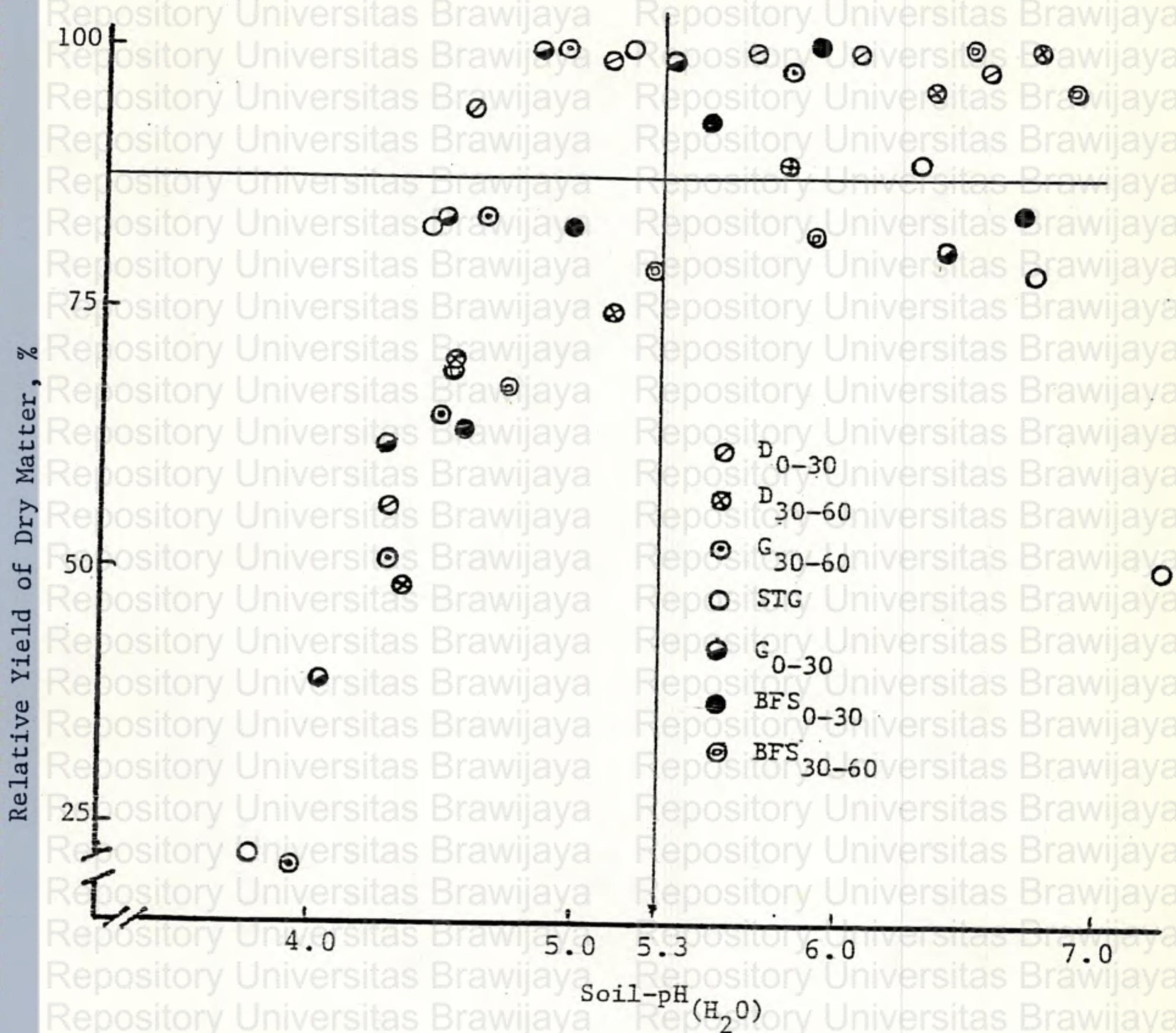

Figure 17. The Relationship between Soil-pH and Relative Yield of Dry Matter of Experimental Hybrid Corn 17x16

The corn plants on the unlimed pots of D_{0-30}, D_{30-60}, STG, G_{0-30}, G_{30-60}, and BFS_{30-60} suffered from severe Al-toxicity. During the first week after emergence, the young leaf tips stuck together and had a watery appearance. The watery tip became dry within the second week of growth. Some of the fibrous roots grew upwards. At the end of the 35 days growing period, the root growth appeared to be restricted to the upper 5 cm soil layer. Lateral roots were damaged, resulting in a knobby appearance. They were easily pulled out, and easily seperated from soil aggregates. Detailed study by Wright and Donahue (1953) used a special staining test to show that aluminum was accumulated on the root surface and in the cortex under conditions of Al-toxicity. In the cortex, the staining occured mostly in the cell protoplasm, sepecially in the nuclei. Little or no staining due to Al-toxicity was found in the conducting tissue inside the endodermis. Microscopic examination on cotton (*Gossypium hirsutum* L.) roots had an abnormally large number of cells with two nuclei in the meristimatic region of the root tip, indicating an inhibition of cell division (Rios and Pearson, 1964). A further assumption had been made that the inhibition of branch root development may be due to reaction of aluminum with the pectic substances of the young cell walls, causing them to lose plasticity prematurely and inhibiting elongation.

The Effect of $CaCO_3$ Application on Nutrient Concentration and Nutrient Uptake by Corn Plants

Nutrient concentration in corn tissue affected by $CaCO_3$ application varied among soils and among elements (Appendix Table 9). A striking effect was primarily observed on calcium content. Calcium concentration increased with increasing $CaCO_3$ application; the most significant increase was observed on pots receiving 0.25 SMP-LR-$pH_{6.0}$ unit level, indicating that the response to Ca^{+2} as a nutrient is likely to occur at very low application levels. This tremendous increase was followed by gradual increase with further addition of $CaCO_3$. Magnesium concentration in corn tissue tended to increase with the first 2-3 levels of $CaCO_3$ treatments, but it decreased or remain unaffected with higher $CaCO_3$ increments; an exception was observed on G_{30-60}, where Mg concentration tended to decrease with increasing $CaCO_3$ levels The first 2 levels of $CaCO_3$ on G_{0-30} and G_{30-60} resulted a significant reduction of Al concentration in corn tissue, but the other five soils used in the experiment did not show a significant Al reduction with increasing $CaCO_3$ levels (Table 16). It seems that Al-concentration in corn tissue above ground portion is unaffected by Al concentration in the soil solution. Solution culture studies showed that increasing Al concentration in solution increased the Al absorption rate by corn plants, but it decreased the portion of absorbed aluminum which was translocated to the above ground portion, resulting in a tremendously high Al concentration in the roots (Anonymous, 1974, p 133). On the contrary, the manganese concentration in corn tissue was drastically reduced, especially by the first level of $CaCO_3$ application. The other elements were inconsistently affected by $CaCO_3$ treatments. Potassium concentration was unaffected by $CaCO_3$ increments. Phosphorus and nitrogen concentrations were below the sufficient range in corn tissue over all $CaCO_3$ levels, indicating that the amounts applied as basal fertilizers were not enough.

Table 16. The Effect of $CaCO_3$ Application on Al-Concentration in Corn Tissue

$CaCO_3$ level	Al uptake on						
SMP-LR-$pH_{6.0}$ unit	D[a/] 0-30	D 30-60	STG	G 0-30	G 30-60	BFS 0-30	BFS 30-60
	(ppm)						
0.00	297	327	206	268	386	202	206
0.25	365	220	156	195	179	160	196
0.50	241	229	176	177	212	150	204
0.75	246	441	152	172	221	129	213
1.00	181	227	168	201	204	160	230
1.25	329	227	170	193	268	168	195
$L.S.D._{0.05}$	N.S.	116	N.S.	79	58	N.S.	N.S.

a/ D = Darmaga, STG = Sitiung, G = Gajruk, BFS = Brown Forest Soil; 0-30 or 30-60 = soil sampled from 0-30 or 30-60 cm depth

To assess the beneficial effect of $CaCO_3$ application on nutrient availability in short term greenhouse experiment such as this, it is best to measure nutrient uptake instead of concentration. The uptake of each element was calculated by multiplying concentration with the corresponding dry matter yield. The average values of nutrient uptake of each element are presented in Appendix Table 10 column 6 to 14. Nutrient uptake of major elements was significantly increased by liming within the 6 levels used. The nutrient uptake by corn plants from the top-layer soils was higher than from the corresponding sub-layer soils (Figures 18-22). The responses for major elements were quadratic for the top-layer soils and linear for the sub-layer soils (Table 17). The simple or the multiple correlation coefficients (r or R) was significant ($P_{0.05}$) to highly significant ($P_{0.01}$). Aluminum uptake on D_{0-30}, D_{30-60}, and Sitiung was insignificantly affected by $CaCO_3$ increments, but it was significantly increased on the other soils (Table 18). Manganese uptake was significantly reduced on D_{30-60}, BFS_{0-30} and BFS_{30-60}, but not on other soils. Zinc uptake was significantly increased on D_{0-30} and BFS_{30-60}, but was insignificantly affected on the other soils. Copper uptake was significantly increased on D_{30-60}, G_{0-30}, BFS_{0-30}, BFS_{30-60}, but insignificantly affected on D_{0-30} and STG.

In general, nutrient uptake by corn plants starts to level off or decrease at $CaCO_3$ application equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit or higher (Appendix Table 10, column 4 to 13; Figure 18 to 22). The magnitude of change varied among soils and among elements. The soils that showed

Table 17. Relationship Between Nutrient Uptake (Y_i) and Levels of $CaCO_3$ Application (X_i)

Soil	Regression equation	R^2-value
	N uptake	
D_{0-30}	$Y = 59.93 + 233.60\ X - 209.03\ X^2$	$0.903^{n.s.}$
D_{30-60}	$Y = 42.12 + 165.51\ X - 135.65\ X^2$	0.954^{*}
	$Y = 57.77 + 516.49\ X - 435.98\ X^2$	0.952^{*}
G_{0-30}	$Y = 58.45 + 199.83\ X - 85.42\ X^2$	0.997^{**}
G_{30-60}	$Y = 20.62 + 114.57\ X - 43.21\ X^2$	0.954^{*}
BFS_{0-30}	$Y = 123.02 + 85.73\ X - 92.64\ X^2$	0.768^{ns}
BFS_{30-60}	$Y = 35.59 + 40.89\ X$	0.840^{**}
	P uptake	
D_{0-30}	$Y = 4.09 + 28.47\ X - 27.78\ X^2$	0.966^{*}
D_{30-60}	$Y = 2.36 + 13.28\ X - 12.02\ X^2$	0.910^{ns}
	$Y = 6.59 + 44.96\ X - 39.22\ X^2$	0.865^{ns}
G_{0-30}	$Y = 3.80 + 31.37\ X - 18.75\ X^2$	0.981^{*}
G_{30-60}	$Y = 1.21 + 5.98\ X$	0.974^{**}
BFS_{0-30}	$Y = 7.98 + 12.95\ X - 12.30\ X^2$	0.993^{**}
BFS_{30-60}	$Y = 2.21 + 6.33\ X - 5.26\ X^2$	0.790^{ns}
	K uptake	
D_{0-30}	$Y = 95.72 + 268.26\ X - 226.06\ X^2$	0.977^{*}
D_{30-60}	$Y = 48.12 + 271.21\ X - 185.89\ X^2$	0.950^{*}
	$Y = 53.81 + 444.41\ X - 345.12\ X^2$	0.971^{*}
G_{0-30}	$Y = 77.17 + 290.33\ X - 188.35\ X^2$	0.978^{*}
G_{30-60}	$Y = 25.41 + 279.63\ X - 127.13\ X^2$	0.997^{**}
BFS_{0-30}	$Y = 203.61 + 350.80\ X - 273.21\ X^2$	0.923^{*}
BFS_{30-60}	$Y = 87.43 + 173.42\ X$	0.948^{**}
	Ca uptake	
D_{0-30}	$Y = 5.93 + 73.75\ X - 42.21\ X^2$	0.993^{**}
D_{30-60}	$Y = 6.02 + 40.17\ X$	0.977^{**}
	$Y = 8.13 + 164.55\ X - 118.75\ X^2$	0.935^{ns}
G_{0-30}	$Y = 4.98 + 50.68\ X - 14.40\ X^2$	0.997^{**}
G_{30-60}	$Y = 4.92 + 25.94\ X$	0.905^{*}
BFS_{0-30}	$Y = 9.60 + 41.29\ X - 19.53\ X^2$	0.991^{**}
BFS_{30-60}	$Y = 5.13 + 30.95\ X - 9.07\ X^2$	0.993^{**}
	Mg uptake	
D_{0-30}	$Y = 5.14 + 37.84\ X - 25.15\ X^2$	0.997^{**}
D_{30-60}	$Y = 3.12 + 14.04\ X$	0.978^{**}
	$Y = 3.34 + 56.69\ X - 39.86\ X^2$	0.990^{**}
G_{0-30}	$Y = 4.31 + 12.32\ X$	0.978^{**}
G_{30-60}	$Y = 2.08 + 4.91\ X$	0.946^{**}
BFS_{0-30}	$Y = 9.60 + 41.29\ X - 19.53\ X^2$	0.991^{**}
BFS_{30-60}	$Y = 3.61 + 4.12\ X$	0.945^{**}

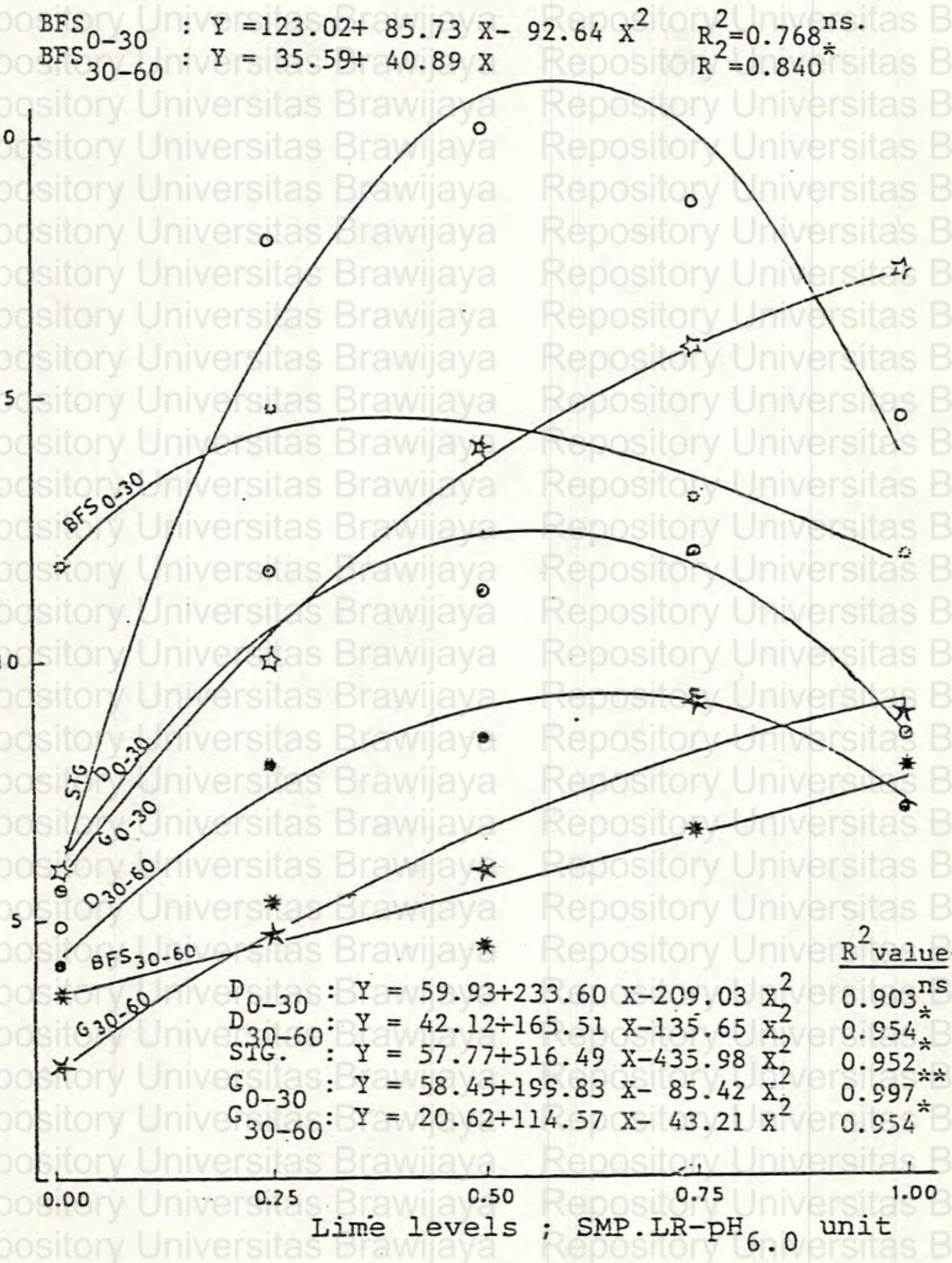

Table 18. The Effect of Lime on N-Uptake by Corn.

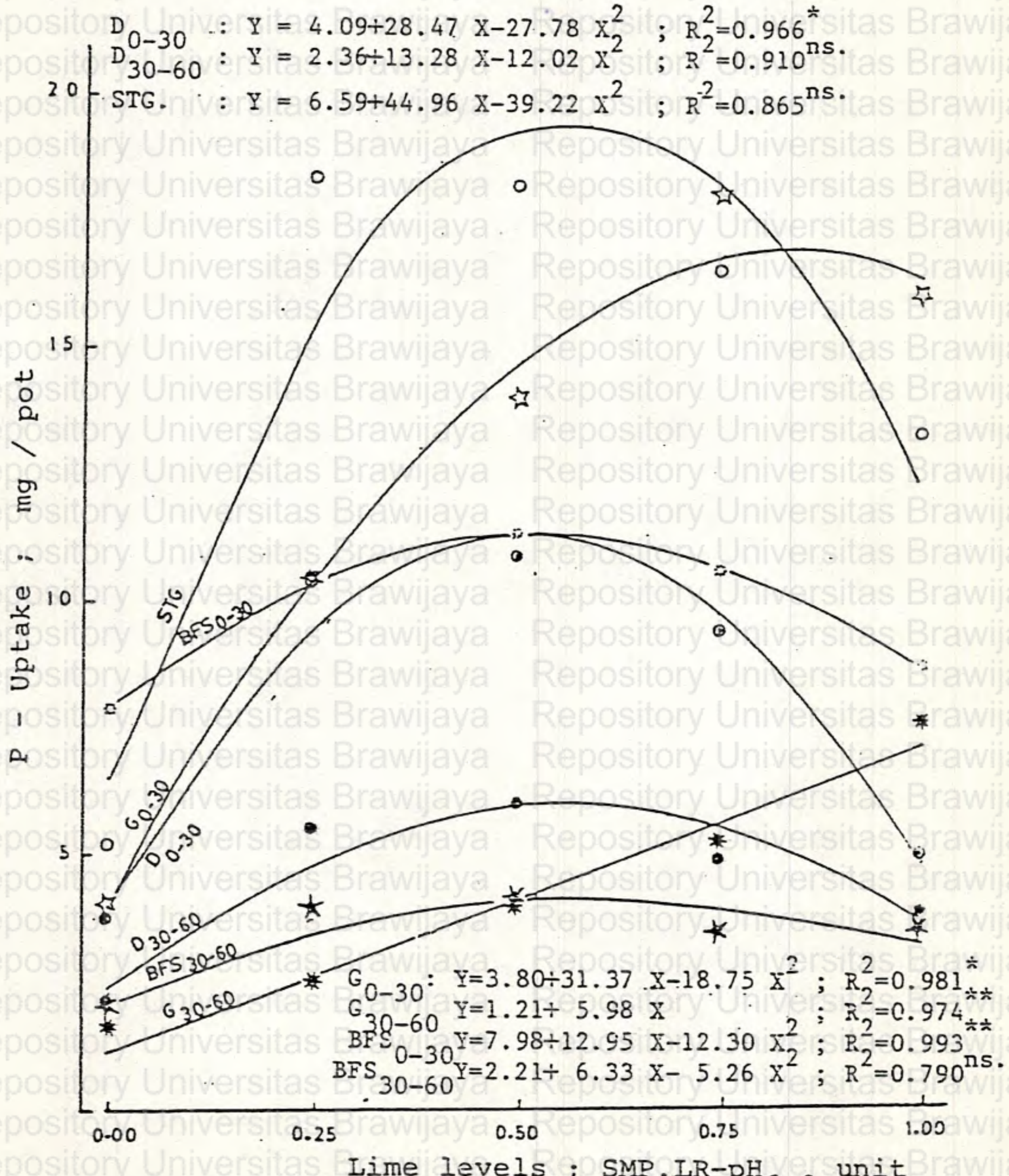

Figure 19. The Effect of Lime on P-Uptake by Corn.

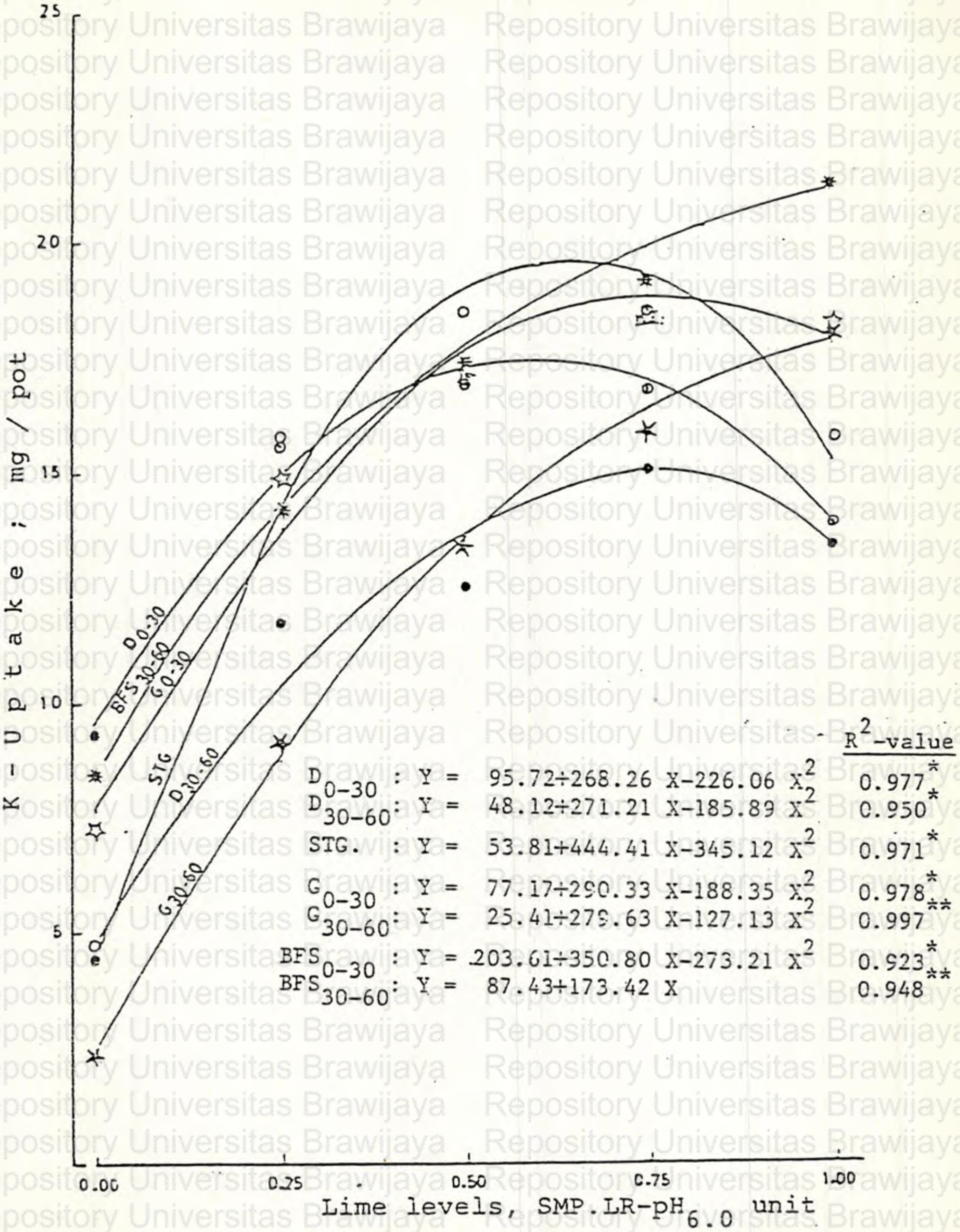

Table 20. The Effect of Lime on K-Uptake by Corn

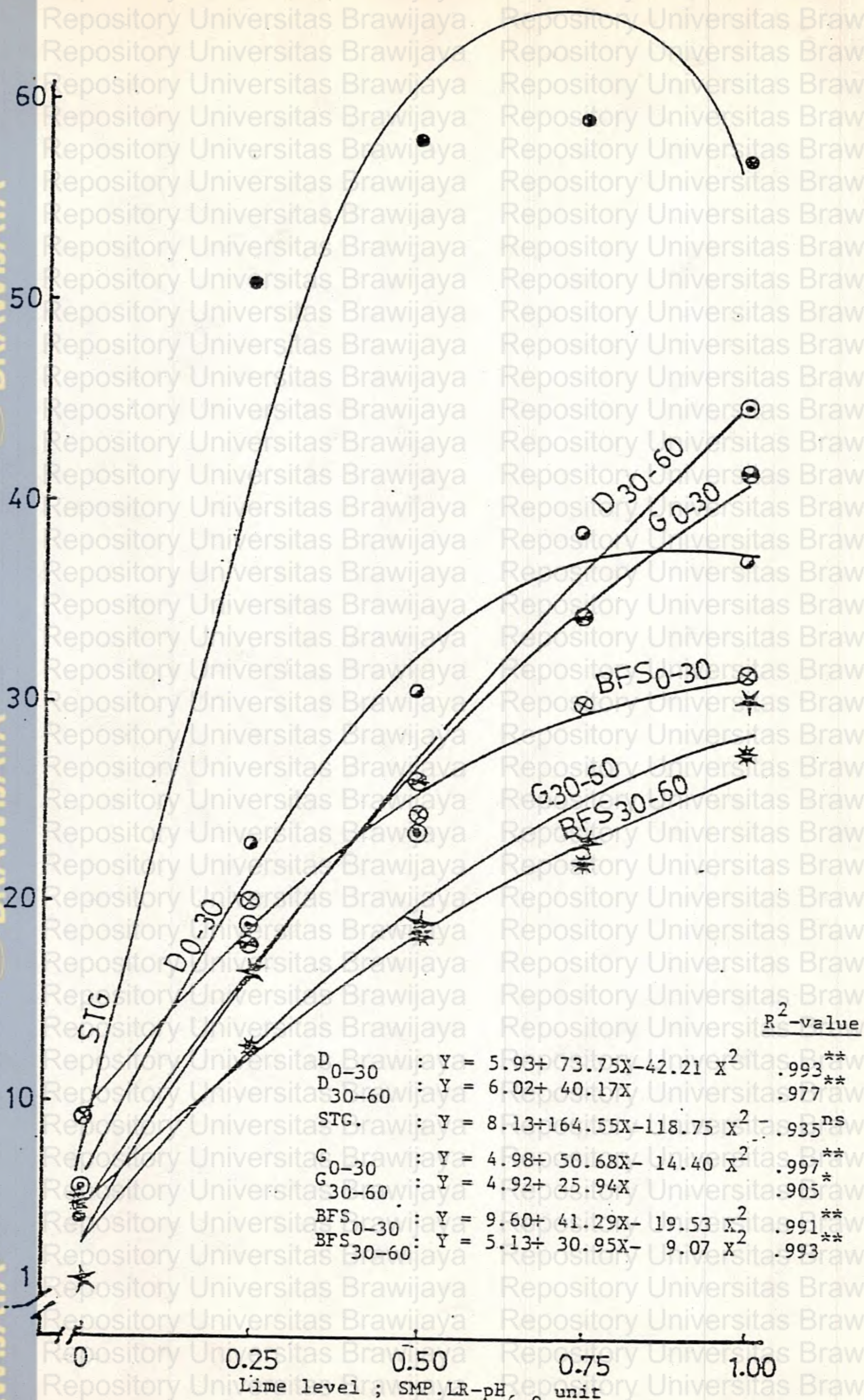

Figure 21. The Effect of lime on Ca-Uptake by Corn

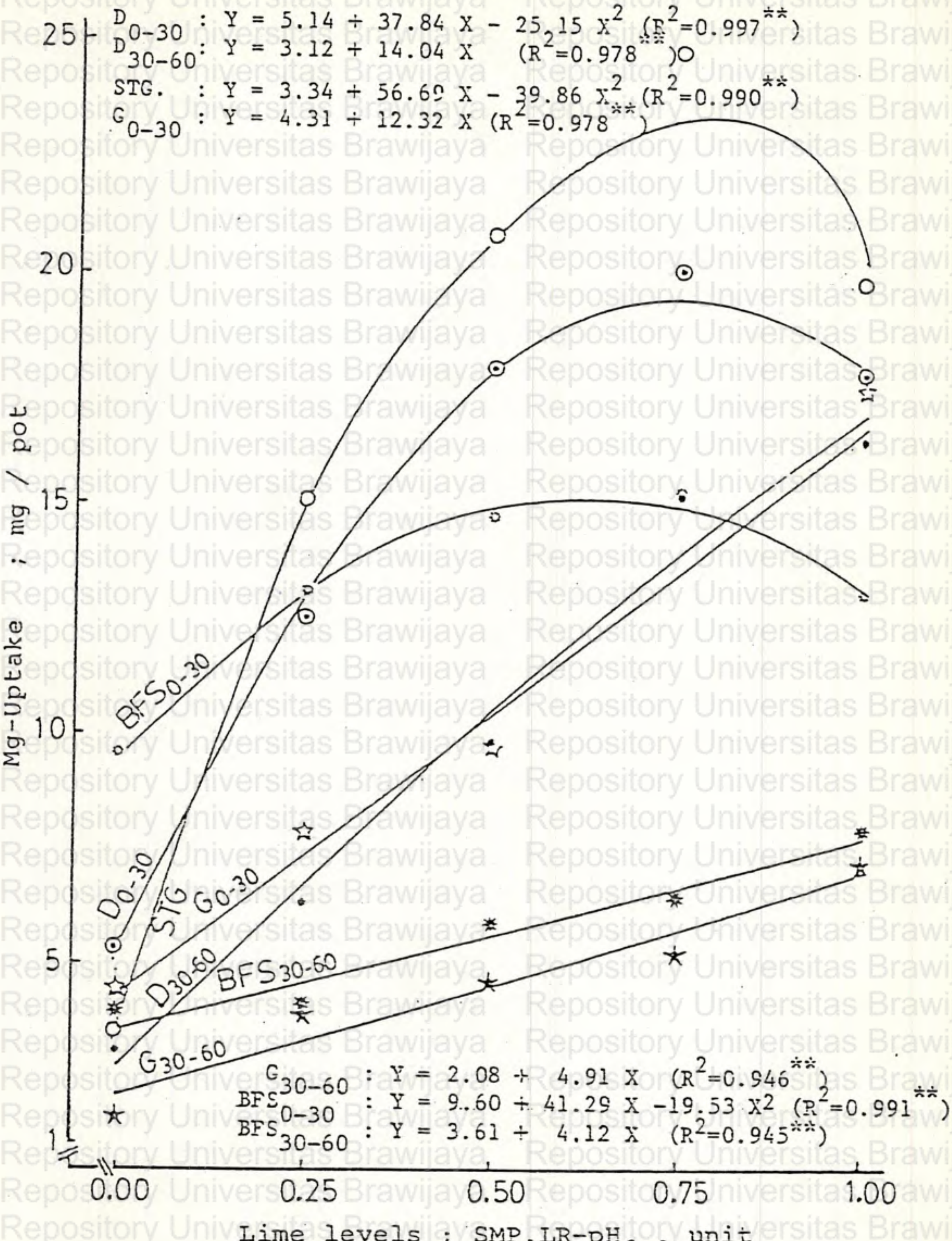

Figure 22. The Effect of Lime on Mg-Uptake by Corn

leveling off or decreasing trends at higher $CaCO_3$ levels have $pH_{(H_2O)}$ value above 6.0 (Appendix Table 10 column 6 to 14). Thus, the overall results indicate that $CaCO_3$ application equivalent to 1.00 SMP-LR-$pH_{6.0}$ test value should be considered as the maximum for liming the acid mineral soils to obtain maximum corn dry matter yield and maximum nutrient uptake.

Table 18. Correlation Coefficients (Simple and Multiple) between Micronutrient Uptake and $CaCO_3$ Treatments

Element	Simple or multiple Corr. Coeff.	Soil						
		D[a/] 0-30	D 30-60	STG	G 0-30	G 30-60	BFS 0-30	BFS 30-60
Al	r	-	N.S.	-	-	0.977**	-	0.913*
	R	N.S.	-	N.S.	0.975*	-	0.993*	-
Mn	r	-	-	-	-	-	-0.999**	-0.936*
	R	N.S.	-0.980*	N.S.	N.S.	N.S.	-	-
Zn	r	-	-	-	-	-	-	0.982**
	R	0.982*	N.S.	N.S.	N.S.	N.S.	N.S.	-
Cu	r	-	-	-	-	0.990**	-	-
	R	N.S.	0.986*	N.S.	0.996**	-	0.989*	0.989*

a/ D = Darmaga, STG = Sitiung, G = Gajruk, BFS = Brown Forest Soil; 0-30 or 30-60 = soil sampled from 0-30 or 30-60 cm depth

N.S. = Not significant at the 5 percent probability level

* = Significant at the 5 percent probability level

** = Significant at the one percent probability level

Soil Chemical Properties *versus* Dry Matter Yield

The soil chemical data clearly show that the amount of soil aluminum as determined by various methods (10^{-2} $\underline{M}$ $CaCl_2$ extractable-Al^{+3}, exch-Al^{+3}, and Al-saturation) change with $CaCO_3$ increments (Appendix Table 10 columns 10, 12, and 14). The effect of these soil properties on dry matter yield were evaluated by performing Cate and Nelson critical value determinations (Cate and Nelson, 1971). The results are presented in Figure 23 to 25. The derived critical values were as follows: (1) the critical value of 10^{-2} $\underline{M}$ $CaCl_2$ extractable-Al is 1.00 ppm Al^{+3}; (2) the critical value of $\underline{N}$ KCl extractable-Al (exch-Al^{+3}) is 0.75 me Al^{+3} /100 g soil; and (3) the critical value of Al-saturation is 17.0 percent. Among the soil-aluminum parameters, the 1.00 ppm Al^{+3} $10^{-2}$$\underline{M}$ $CaCl_2$ extractable aluminum or the 17.0 percent Al-saturation critical value are equally good as soil-aluminum parameters to be utilized as a "safeguard" for liming acid mineral soils, especially in obtaining optimum dry matter yield of corn.

It is certain that aluminum plays an important role in the negative effect of soil acidity to dry matter yields and nutrient uptake by corn plants in the greenhouse experiment. This can be easily seen in Figures 23, 24, and 25 for pots receiving the same amount of basal fertilizers but no lime. When the amount of aluminum accounted for was at least

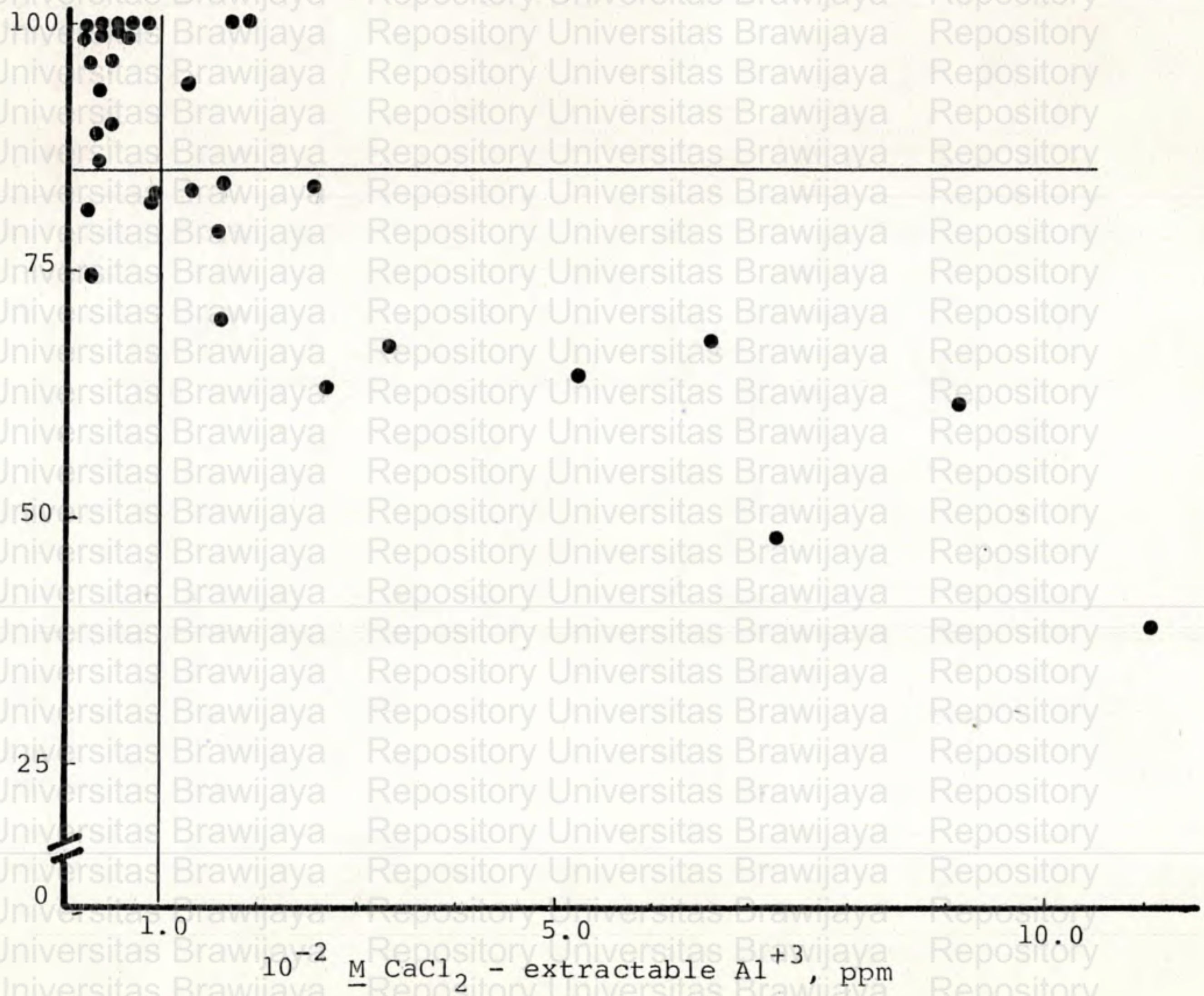

Figure 23. Cate-Nelson Plot for 10^{-2}M $CaCl_2$-Ext-Al^{+3} *vs* Relative Yield as Affected by $CaCO_3$ Application

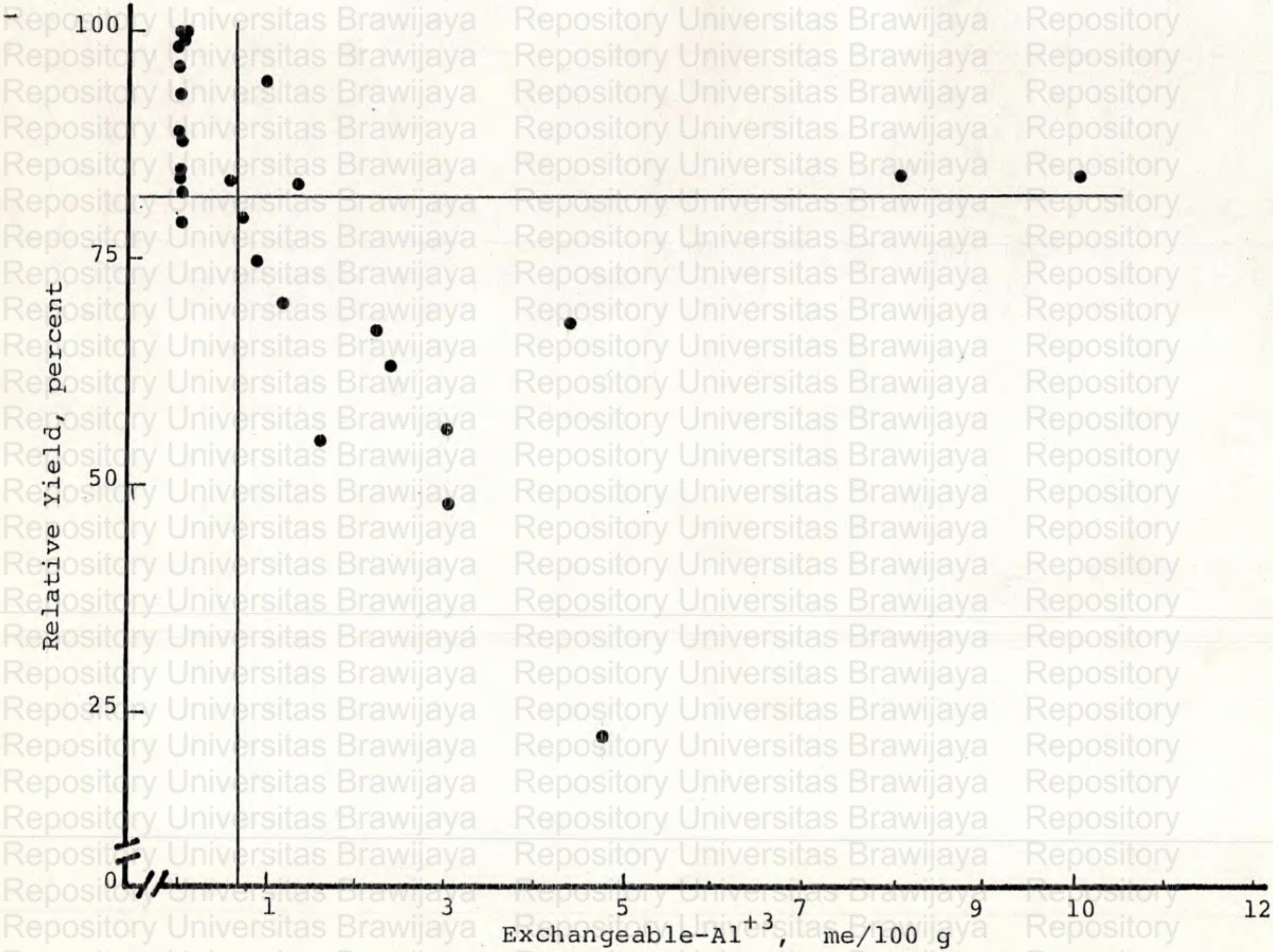

Figure 24. Cate-Nelson Plot for Exch-Al^{+3} *versus* Relative Yield as Affected by $CaCO_3$ Application

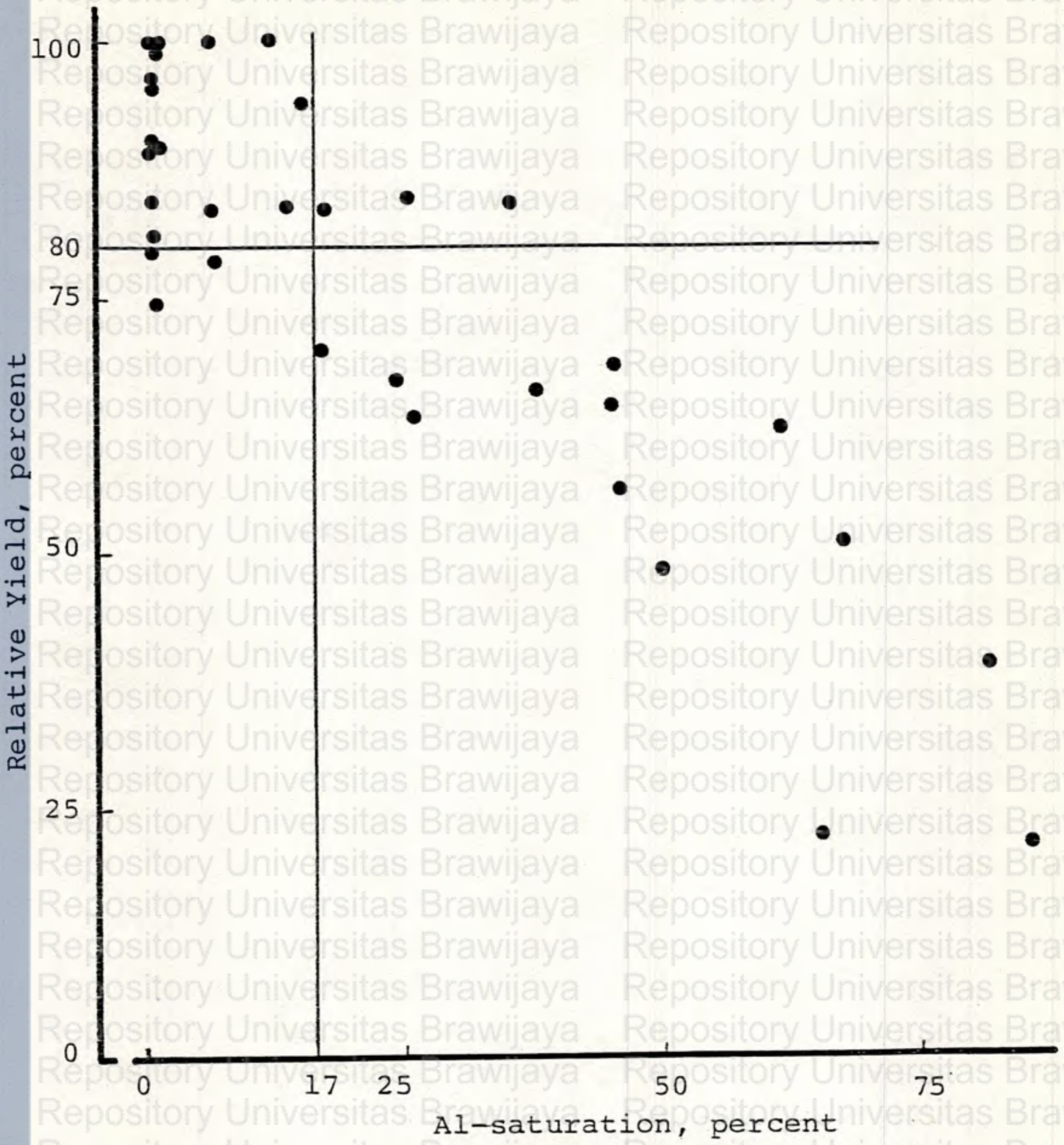

Figure 25. Cate-Nelson Plot for Al-saturation *versus* Relative Yield as Affected by $CaCO_3$ Application

seventeen percent of the exchange cations, dry matter yield starts to decrease drastically for the acid mineral soils studied.

As would be expected from the reciprocal relationship of exch-Al^{+3} and exchangeable bases, dry matter yields on these acid mineral soils varies directly with this characteristic, eighty percent or higher of maximum dry matter yield is achieved when the exch-(Ca+Mg) is a minimum of 9.0 me/100 g soil (Figure 26) or when the exchangeable $K/\sqrt{(Ca+Mg)}$ ratio is less than 15.3×10^{-2} (Figure 27).

The overall soil chemical property relationships and plant chemical property relationships with dry matter yield do not explain the possible cause of dry matter yield reduction when soil-$pH_{(H_2O)}$ was increase beyond 6.0. The postulated answer frequently reported by several workers was lime-induced micronutrient deficiencies that cause reduction in crop yield (Corey et al, 1971; McLean, 1971).

The efficiency of nutrient uptake by corn plants in response to $CaCO_3$ application was evaluated by comparing nutrient uptake of the lime-treated pots *versus* that of the unlimed pots. The results were tabulated in Appendix Table 11, and the average value for each $CaCO_3$ level for all soils was presented in Table 19. The result indicates that $CaCO_3$ application equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit resulted an average of 150 percent increase of N-, P-, K-, Mg-, Zn-, Cu-, and Al-uptake. Calcium uptake was increased

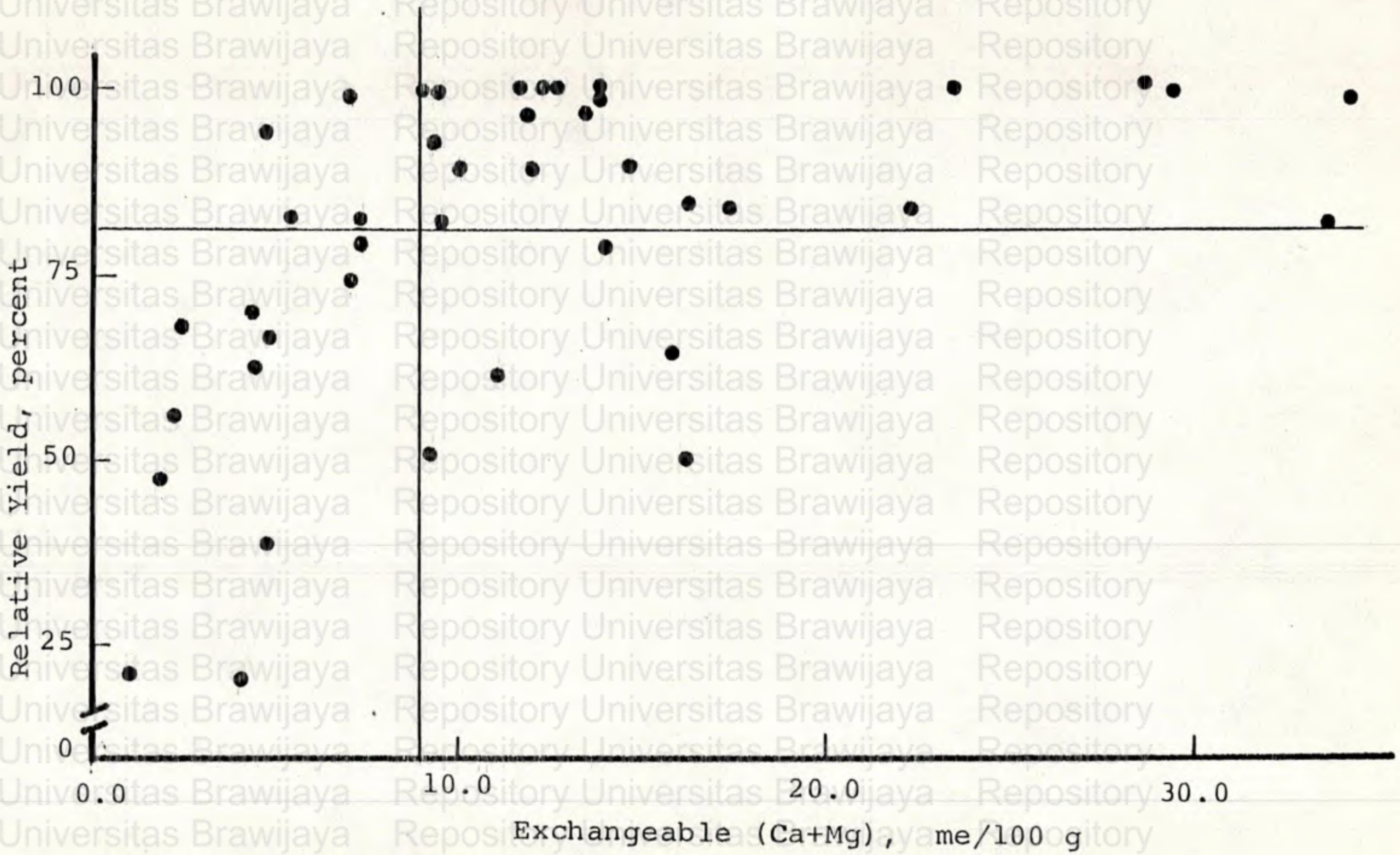

Figure 26. Cate-Nelson Plot for Exch-(Ca+Mg) *versus* Relative Yield as Affected by $CaCO_3$ Application

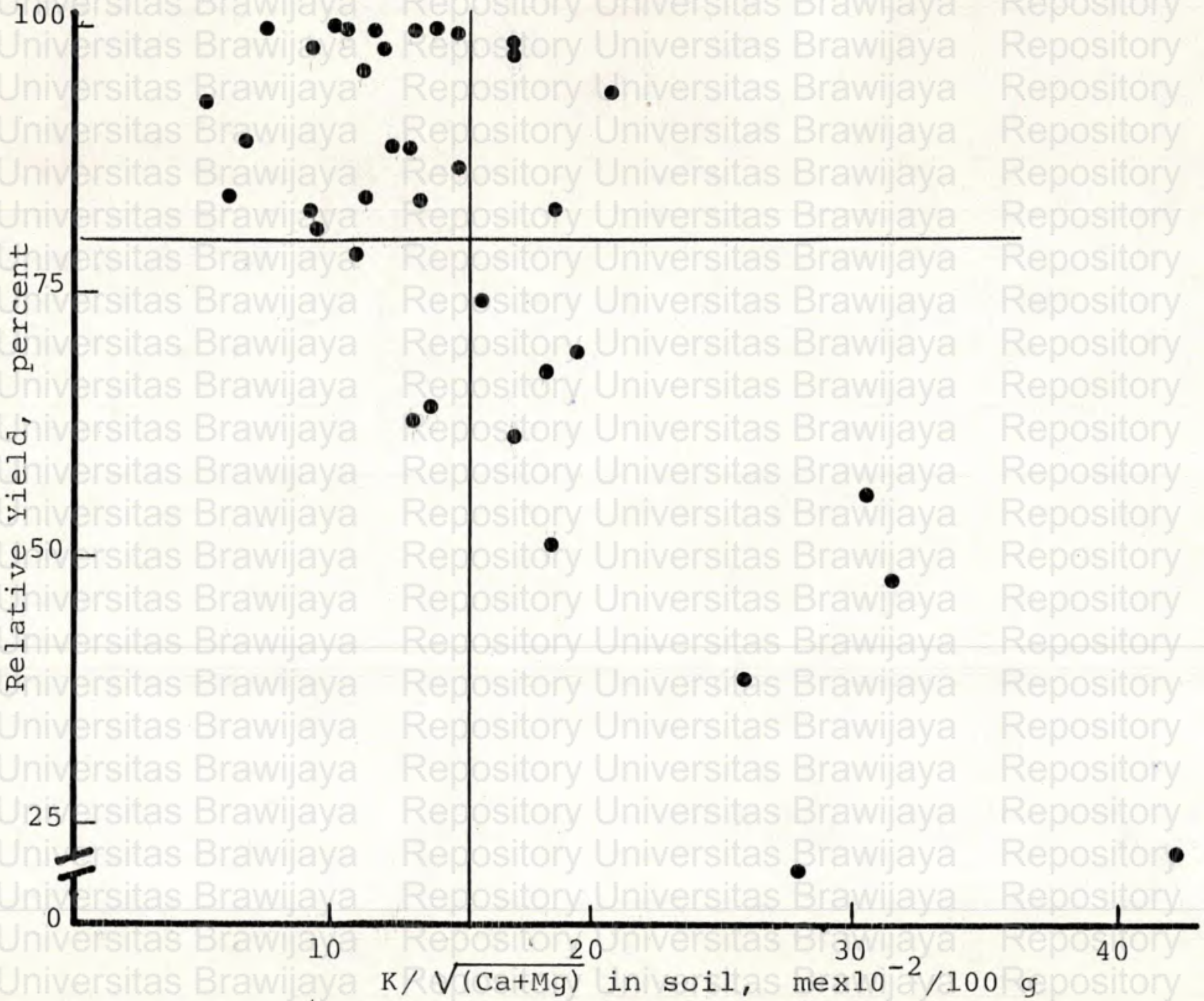

Figure 27. Cate-Nelson Plot for $K/\sqrt{(Ca+Mg)}$ Ratio *versus* Relative Yield as Affected by $CaCO_3$ Application

up to 800 percent, while Mn-uptake was reduced slightly.

Table 19. Average Nutrient Uptake Efficiency Index of Corn in Response to $CaCO_3$ Application

Element	Nutrient uptake efficiency index per $CaCO_3$ level				
	0.00[a/]	0.25	0.50	0.75	1.00
N	100	206	226	261	236
P	100	236	271	273	252
K	100	224	283	319	309
Ca	100	656	801	975	1 128
Mg	100	217	292	355	367
Mn	100	99	104	84	76
Zn	100	169	180	182	177
Cu	100	197	224	267	302
Fe	100	169	210	201	247
Al	100	157	182	195	182

a/ This numerical figure represents the SMP-lR-$pH_{6.0}$ unit value

Greenhouse Experiment-II

Dry Matter Yield Response

Corn dry matter yield response to $CaCO_3$ treatments and depth of $CaCO_3$ application was evaluated at two stages of growth, 35 and 45 days after planting. The yield data are presented in Appendix Table 12.

The lowest dry matter yields were obtained on the unlimed pots receiving the same amount of basal fertilizers as the limed pots. The analysis of variance of the limed pots showed that the effects of $CaCO_3$ increments and depth of $CaCO_3$ application on dry matter yields, harvested at

35 or 45 days after planting, were significant at the one percent probability level, and there was no interaction between $CaCO_3$ increments and depth of $CaCO_3$ application on dry matter yields (Table 20). Dry matter yield response to $CaCO_3$ increments applied in the first 20 cm toplayer was higher than to those applied in the first 20 cm toplayer. The corn plants on pots limed in the first 20 cm developed a better root system; the roots grew deeper. The dry matter yield response showed a quadratic property (Figure 28 and 29).

Table 20. Dry Matter Yield Responses at Two Growing Stages to $CaCO_3$ Increments and Depth of $CaCO_3$ Applications

Soil	Growth stage (days)	F-ratio value		
		$CaCO_3$ effect	Depth of appl. effect	Interaction
Latosol Darmaga	35	**	N.S.	N.S.
	45	**	*	N.S.
Podzolic Gajruk	35	**	**	N.S.
	45	**	**	N.S.

* = Significant at the 5 percent probability level
** = Significant at the 1 percent probability level
N.S.= Nonsignificant at the 5 percent probabulity level

When dry matter yield response is related to the corresponding $pH_{(H_2O)}$ changes affected by $CaCO_3$ increments, it clearly indicates that the greatest dry matter yield response occured when soil-$pH_{(H_2O)}$ was increased to 5.32.

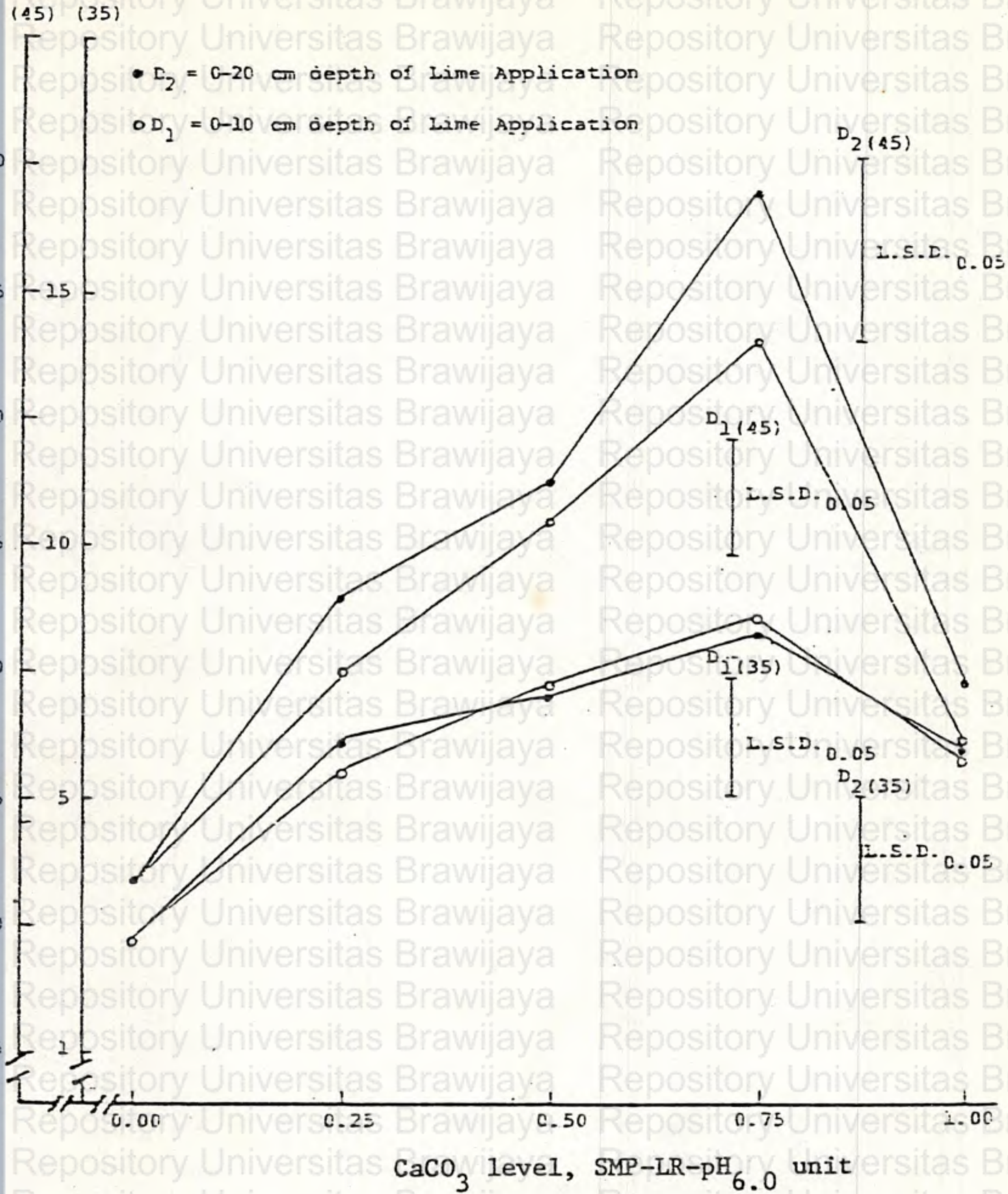

Figure 28. Corn Dry Matter Yield Response to $CaCO_3$ Increments and Depth of $CaCO_3$ Application: Latosol Darmaga

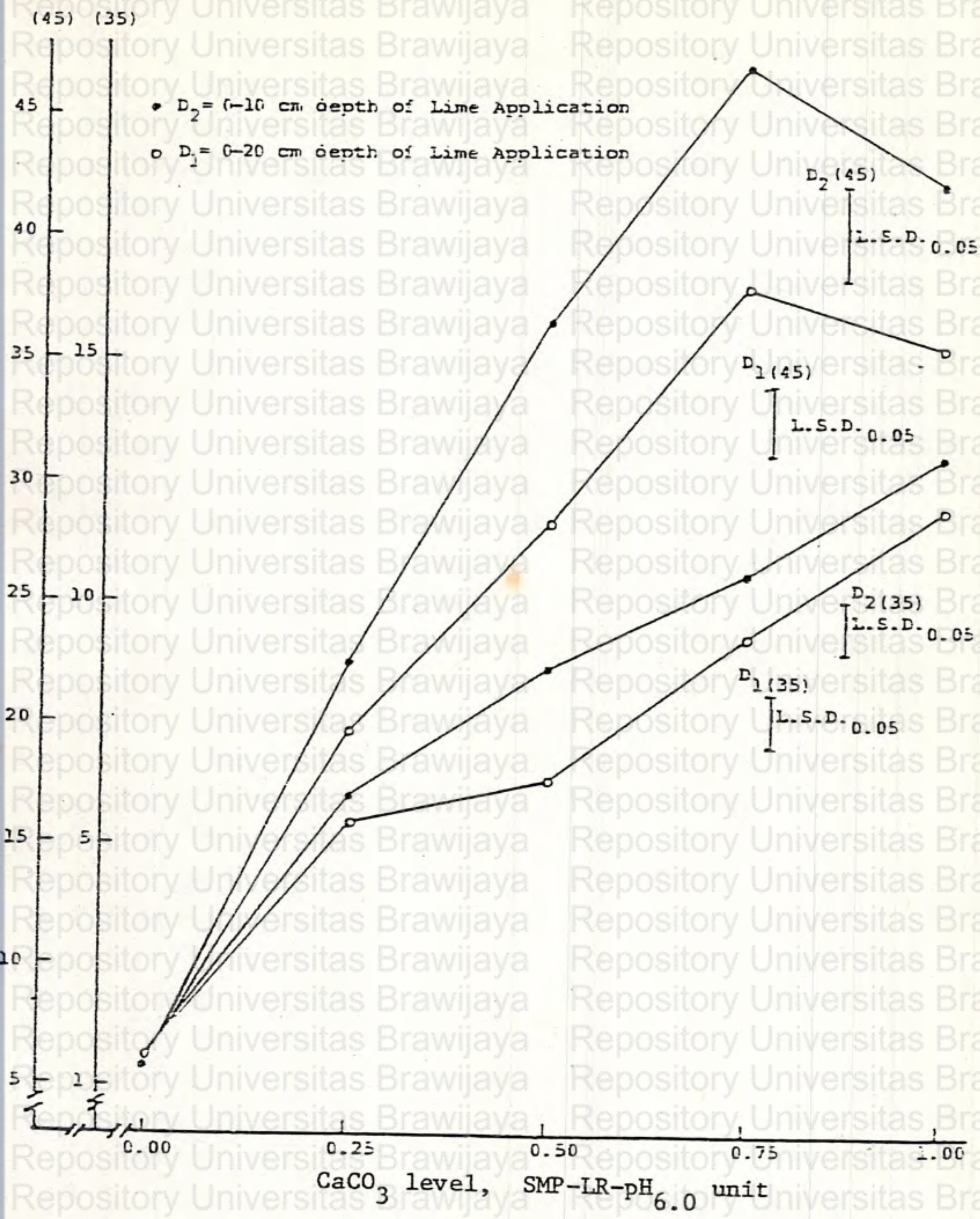

Figure 29. Corn Dry Matter Yield Response to $CaCO_3$ Increments and Depth of $CaCO_3$ Application: Podzolic Gajruk

The highest dry matter yield was obtained within soil-pH$_{(H_2O)}$ range of 5.5 to 6.0 (Figure 30). The same results were reported by Juo and Ballaux (1977).

Root Growth and Development

The effect of $CaCO_3$ treatments and depth of $CaCO_3$ application on root growth and development was evaluated qualitatively. Observation through the glass window (Figure 1) was carried out during the 45 days period, and at the end of this growing period, showed that root growth in the unlimed soils was severely restricted to the upper 5 cm soil layer. The first $CaCO_3$ level, equivalent to 0.25 SMP-LR-pH$_{6.0}$ unit, resulted in extensive root development within the limed layer. The roots which were able to penetrate into the unlimed subsurface layer exhibited a typical Al-toxicity symptoms; severe stunting, thickening of roots, and suppression of lateral roots, resulting in a knobby appearance (Figure 31). The pictures presented in Figure 31 clearly show that application of 500 ml of deionezed water daily during the 45 days growing period was insignificant in its effect on Ca movement into the unlimed subsurface soil layer, though there is a possibility of differential movement of Ca within the layer and subsequently into the the unlimed subsurface layer as reported by Juo and Ballaux (1977). Probably, the added $CaCO_3$ is first consumed to create negative sites, and these sites in turn is balanced by

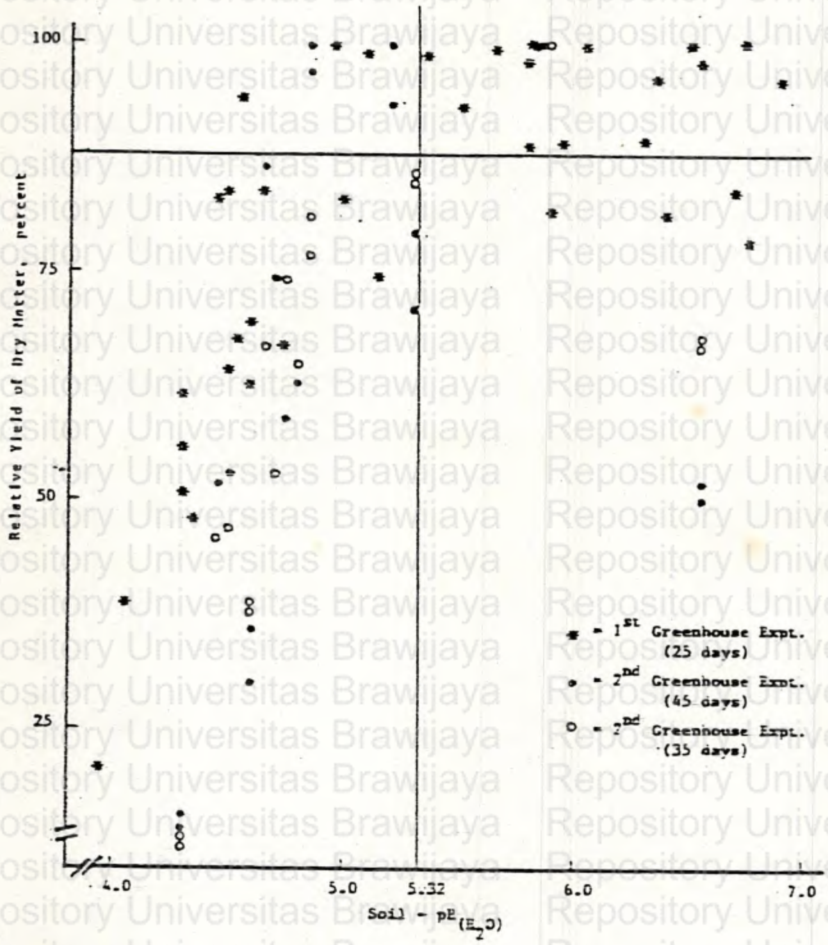

Figure 30. Cate-Nelson Plot for Soil-pH *versus* Relative Yield Affected by $CaCO_3$ Application (Pot Experiments I and II)

calcium ions at the sites of $CaCO_3$ application, so that very few or no calcium ions move into the unlimed subsurface layer.

It appears advisable to incorporate lime as deeply as possible for reducing the "barrier" function of aluminum in the subsurface soil to root growth and proliferation. It is recommended to incorporate lime by rotovation to 30 cm in order to reduce aluminum to this depth. This will result in the development of root system which is effective in absorbing more water during ocasional periods of dry weather (Abruna et al, 1975).

Field Experiments

Latosol from Darmaga

The increase in corn yields in response to calcitic limestone application is tabulated in Appendix Table 12. The analysis of variance of the completely randomized block design is presented in Appendix Table 13, and the corresponding response curve is presented in Figure 32.

The experimental results show that the response is quadratic, significant at the one percent probability level. The control plots which received 1.33 ton of calcitic limestone yielded an average of 76 percent of the maximum yield, and yet higher lime increments were able to increase grain yields significantly. The maximum yield was obtained with

8.10 ton of calcitic limestone per hectare or equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit value, and further lime increments caused a significant reduction in yields (Table 21).

Table 21. Corn grain Yields in Response to Calcitic Limestone Application on Latosol from Darmaga

Lime level[a/]	Equivalent to SMP-LR-$pH_{6.0}$ unit	Grain yield[b/]
(ton/Ha)		(ton/Ha)
1.33	0.125	3.83
2.67	0.25	4.34
5.33	0.50	4.60
8.00	0.75	5.05
10.67	1.00	4.56
13.33	1.25	4.24
L.S.D.$_{0.05}$		0.35

a/ Lime material used was calcitic limestone (80 mesh). The $CaCO_3$ equivalent value was 98 percent.

b/ Grain yield was an average of 8 replications, and based on population density of 50 thousand plants per hectare

Podzolic Soil from Jonggol

The increase in corn grain yields in response to calcitic limestone and P applications is tabulated in Appendix Table 13. The analysis of variance is presented in Appendix Table 14, and the corrsponding response curve is presented in Figure 32.

The experimental result showed that there was no P effect on corn grain yields. The highest P level used

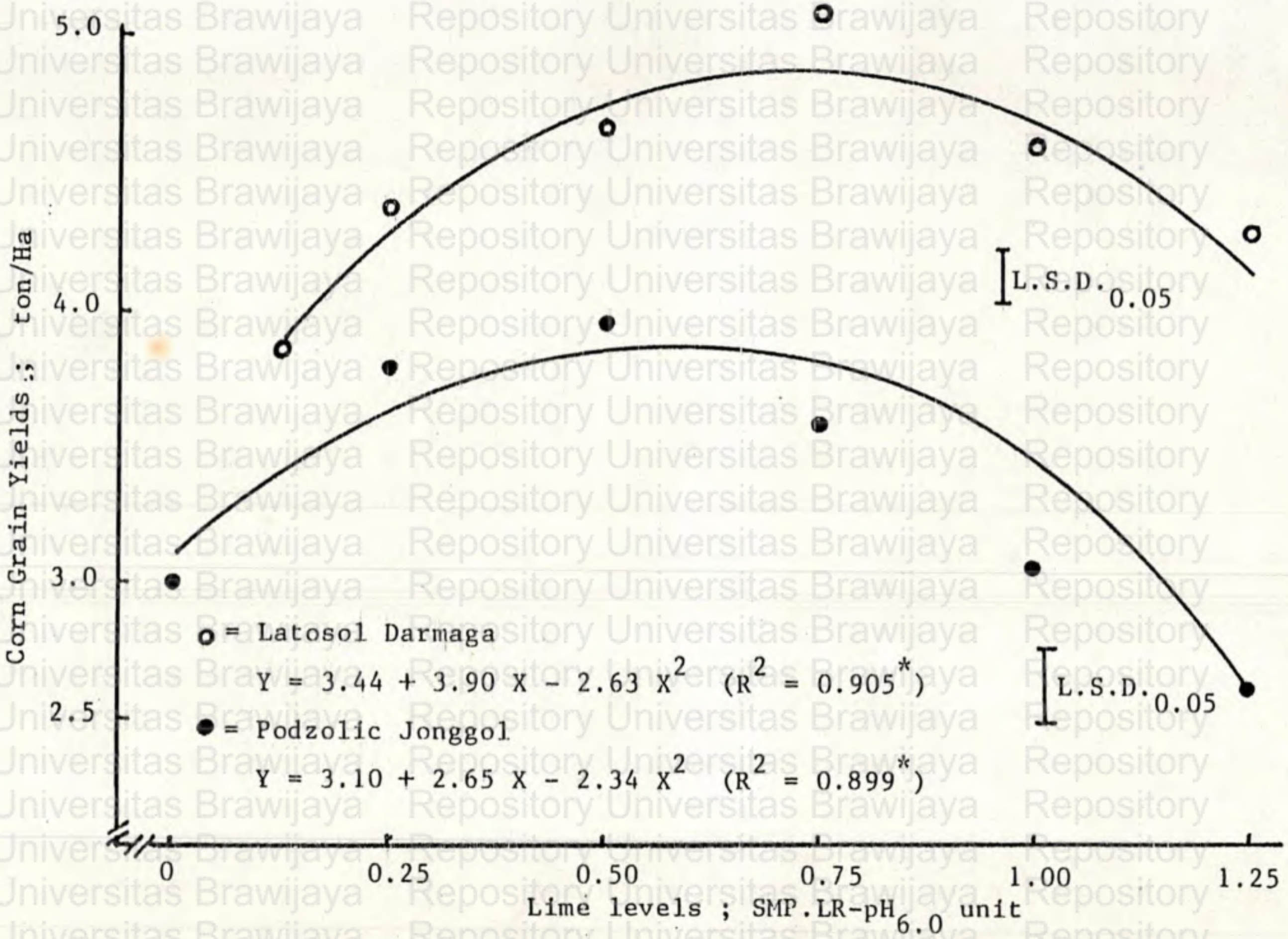

Fig. 32: The Effect of Lime Application on Corn Grain Yields
(Field Trials)

(225 kg P/Ha) or equivalent to 1.14 ton TST (19.8 % P) could not overcome the the detrimental effect of aluminum on corn grain yield. On the contrary, the effect of calcitic limestone application was highly significant, and it showed a quadratic relation with grain yields (Figure 32). Corn yield on the unlimed plots over all P levels was 76 percent of the maximum yield obtained. The maximum yield response was obtained with 9.64 ton calcitic limestone per hectare or equivalent to 0.50 SMP-LR-$pH_{6.0}$ unit value, and that further increments resulted a significant yield reduction (Table 22).

Table 22. Corn grain Yields in Response to Calcitic Limestone Application on Podzolic Soil from Jonggol

Lime levels[a/]	Equivalent to SMP-LR-$pH_{6.0}$ unit	Grain yield[b/]
(ton/Ha)		(ton/Ha)
0.00	0.00	2.97
4.82	0.25	3.77
9.64	0.50	3.93
14.46	0.75	3.54
19.28	1.00	3.00
24.10	1.25	2.58
L.S.D.$_{0.05}$		0.31

a/ Lime material was calcitic limestone. The $CaCO_3$ equivalent value = 98 percent

b/ Grain yield was an average of 9 plots, based on population density of 50 thousand plants per hectare

The overall results on both locations show that lime application equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit should be considered as the maximum amount needed in obtaining optimum yield of corn variety H-6.

SUMMARY AND CONCLUSION

Laboratory, greenhouse, and field expeirments were conducted to study various aspects of lime application in relation to sustaining better crop growth and production on acid mineral soils in Indonesia.

The first objective was to evaluate relationships between soil-pH and other soil chemical changes affected by lime application. Twinty-eight acid mineral soils, each receiving 6 levels of pure reagent grade $CaCO_3$ powder, incubated at field moisture capacity in plastic bags, were stored at room temperature for 30 days. After 30 days, sub-samples were taken for laboratory analysis. The selected chemical analyses were: pH, TAc, exch-Ac, exch-Al^{+3}, Al-saturation, CEC, ECEC, and base saturation.

The following summary statements can be made concerning those comparisons.

1. The rate of pH change per $CaCO_3$ increment varies among soils. The scatter diagrams of $CaCO_3$ levels and pH show that each soil exhibits several buffering capacity ranges within the $CaCO_3$ levels used, indicating that the higher the exch-Al^{+3} content the higher the amount of lime required to raise soil-pH to the desired pH value.

2. Liming to a desired $pH_{(H_2O)}$ of 5.5 causes a drastic reduction in TAc, exch-Al^{+3}, Al-saturation, and exch-Ac.

The drastic reduction of these soil properties exhibit curvilinear characteristics. The higher the exch-Al^{+3} the higher the reduction rate per unit drop in pH below 5.5, and the differences in exch-Al^{+3} or Al-saturation among the soils are greatly deminished or nullified at soil $pH_{(H_2O)}$ 5.5 or higher. Only 5 percent of exchange sites are occupied by aluminum at soil-$pH_{(H_2O)}$ 5.5 or 92.5 percent of exch-Al^{+3} is neutralized.

3. Titratable acidity or permanent charge acidity and partially pH-dependent charge acidity are deprotonated by liming, resulting in additional net negative sites. Thus, the CEC or base saturation increases accordingly. Base saturation based on CEC increases linearly with increasing pH within the $CaCO_3$ levels used. The increase in base saturation based on ECEC exhibits an assymptotic relationship with increasing pH. The higher the exch-Al^{+3} content of the soil the higher is the reduction of BS_2 per unit pH drop below 5.5; at soil $pH_{(H_2O)}$ 5.5 and soil-$pH_{(H_2O)}$ 6.0, the effective base saturation reaches 82.5 and 92.5 percent, respectively.

The second objective was to devise one or more lime requirement (LR) test(s) based on selected soil properties or made some modification of the existing buffer methods. The buffering curves of incubated soil samples with $CaCO_3$ for 30 days and for 12 months were used to derive the $CaCO_3$-determined LR test values. The $CaCO_3$-determined LR at desired soil-$pH_{(H_2O)}$ 5.5 and 6.0 were used as the reference LR test, and were assigned as the $CaCO_3$-LR-$pH_{(H_2O)5.5}$ and $CaCO_3$-LR-$pH_{(H_2O)6.0}$. The other lime requirement tests were: SMP-LR-$pH_{6.0}$, SMP-DB-LR-$pH_{6.0}$, Yuan-DB-LR-$pH_{6.0}$, and the LR test based on soil properties. The soil properties were obtained from the original soils. The regression equations relating to these LR tests with the reference LR tests were also determined. The significant contribution of soil properties to LR was evaluated by simple and multiple regression analyses.

The following summary statements can be made concerning these comparisons.

1. Either $CaCO_3$ or $Ca(OH)_2$ of pure reagent grade powder is equally good as a liming material for determining the reference LR tests for testing the reliability of the other lime requirement tests.

2. The $CaCO_3$-LR-$pH_{(H_2O)5.5 \text{ or } 6.0}$ is highly correlated with the corresponding $CaCO_3$-LR-$pH_{(KCl)2 \text{ or } 1}$. The correlation coefficients are 0.989^{**} or 0.999^{**}, respectively.

3. The SMP-LR-$pH_{6.0}$ as determined from the original table of Shoemaker <u>et al</u> (1961) correlates better with the two reference LR tests for acid mineral soils having Al-saturation less than 30 percent than for acid mineral soils having aluminum saturation higher than 30 percent.

4. The SMP-DB-LR-pH$_{6.0}$ is less suitable for estimating lime requirement of the soils than the SMP-LR-pH$_{6.0}$. The correlation coefficient is 0.830** *versus* 0.973**, respectively. The Yuan-DB-LR-pH$_{6.0}$ is also less suitable than the SMP-LR-pH$_{6.0}$. Furthermore, both double methods require laborous laboratory work and calculations.

5. Percentage organic matter is the dominant contributor ot LR for acid mineral soils having Al-saturation less than thirty percent, followed by exch-Ac and nonexch-Al. The corresponding coefficient of determination of the best fit multiple regression equations are smaller than the SMP-LR-pH$_{6.0}$ relationships to both reference LR tests. Thus, the best fit regression equations to assess LR of acid mineral soils having Al-saturation less than 30 percent are:

$$LR_{pH(H_2O)5.5} = - 1.34 + 0.71\ \text{SMP-LR-pH}_{6.0} \quad (r = 0.960^{**})$$

$$LR_{pH(H_2O)6.0} = - 0.47 + 0.90\ \text{SMP-LR-pH}_{6.0} \quad (r = 0.974^{**})$$

6. Exchangeable aluminum is the dominant contributor to lime requirement of acid mineral soils having Al-saturation higher than 30 percent. The corresponding correlation coefficients are higher than the SMP-LR-pH$_{6.0}$ correlation coefficients with the same reference LR tests. Therefore, the best fit regression equations to assess LR of acid mineral soils having Al-saturation higher than 30 percent are:

$$LR_{pH(H_2O)5.5} = 5.71 + 0.70 \text{ exch-Al}^{+3} \quad (r = 0.971^{**})$$

$$LR_{pH(H_2O)6.0} = 7.53 + 0.85 \text{ exch-Al}^{+3} \quad (r = 0.974^{**})$$

The third objective was to evaluate dry matter yield, and nutrient uptake by corn plants (*Zea mays* L.) in response to lime application. Dry matter yield was also related to soil chemical property changes affected by lime application. To accomplish this objective, a greenhouse experiment was conducted using top- and subsurface-samples from different acid mineral soils. Each soil received six levels of pure reagent grade $CaCO_3$ powder, incubated at 100 percent field moisture capacity for 30 days, and then air dried. Basal nutrient solution was sprayed onto soil aggregates, and incubated at 100 percent FMC for an additional 10 days. Subsamples were taken for chemical analyses before the soils were put in 1.0 kg capacity plastic pots. Experimental hybrid corn 17x16 was used, planted 1.5 cm deep and thinned to three plants per pot after emergence. The corn plants were harvested 35 days after planting, oven dried, ground, and analyzed.

The following summary statements can be made concerning those responses.

1. Dry matter yields are significantly affected by $CaCO_3$ applications. The yield response varies among soils used. The largest increase occurs with lower levels of $CaCO_3$

application, and the maximum response is obtained at higher levels within the 0.50 to 1.00 SMP-LR-$pH_{6.0}$ unit range.

2. The largest dry matter yield increase is obtained when soil-$pH_{(H_2O)}$ is increased to 5.3, and the maximum yield response occurs within $pH_{(H_2O)}$ 5.5 to 6.0

3. Nutrient uptake by corn plants starts to level off or decreases at $CaCO_3$ levels equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit or higher, and the magnitude of response varies among soils and among elements. The soils which show a leveling off or decreasing trend in nutrient uptake at higher $CaCO_3$ levels have $pH_{(H_2O)}$ values higher than $pH_{(H_2O)}$ 6.0

4. Dry matter yield is negatively related to 10^{-2} $\underline{M}$ $CaCl_2$ extractable-Al content, exch-Al^{+3} content, and Al-saturation. The critical values obtained from the Cate-Nelson plots are 1.00 ppm Al^{+3}, 0.75 me Al^{+3}/100 g soil, and 17.0 percent, respectively. Each one of these soil-aluminum measures can be utilized as a "safeguard" for liming acid mineral soils in Indonesia

5. As would be expected from the reciprocal relationship of exch-Al^{+3} and exch-bases, dry matter yields vary directly with this characteristics. When exch-(Ca+Mg) is 9.0 me/100g of soil or when the exchangeable $K/\sqrt{(Ca+Mg)}$ ratio is less 15.3×10^{-2}, a minimum of 80 percent of maximum dry matter yield of corn is obtained.

6. The nutrient uptake efficiency index evaluation shows that $CaCO_3$ application equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit resulted an average increase of 150 percent in N, P, K, Mg, Zn, Cu, and Al uptake by corn plants at the 30 day growing period. Calcium uptake efficiency index is increased up to 800 percent, while that of Mn is reduced slightly.

Corollary to the above objectives was the need to evaluate root growth and development of corn plants in response to $CaCO_3$ increments and depth of $CaCO_3$ application. A greenhouse experiment was conducted using two different acid mineral soils; each was sampled from 0-30 and 30-60 cm soil depth, and designated as top- and subsurface-layers, respectively. The untreated air dried subsurface layer soil samples were placed in locally made plywood pots at depths of 30-50 cm. The top-layer soil samples were placed on top of the subsurface soil at depth of 0-20 cm after receiving a factorial combination of lime and depth of lime treatments. The $CaCO_3$ levels were equivalent to 0.00, 0.25, 0.50, 0.75, and 1.00 SMP-LR-$pH_{6.0}$ units, respectively. The depth of $CaCO_3$ application were 0-10 and 0-20 cm, respectively. Incubation with $CaCO_3$ lasted for 30 days and an additional ten days of incubation allowed after basal nutrient solution application. Sub-samples were taken before placing the soils in the assigned pots. Five hundred milliliters of deionezed water was added daily. The soils were planted with experimental hybrid corn 17x16, one plant at the center and one plant at 5 cm from the glass window. The plants near the glass window were harvested at 35 days and those at the center were harvested at 45 days after planting, respectively. Root growth and development were qualitatively studied during the 45 day period by visual observation through the glass window. Whenever no observation being done, the glass window was covered with a black plastic sheet. At the end of the 45 day period, the glass windowed side wall was opened, soil aggregates were seperated from root surfaces by a gentle tap-water spraying. Several pictures were then taken.

The following summary statements can be made concerning the experiment.

1. Dry matter yields are higher when $CaCO_3$ is incorporated at 0-20 cm than at 0-10 cm soil depth.

2. The largest dry matter yield response is obtained when soil-pH$_{(H_2O)}$ is raised to 5.32, and the highest yield response occurs within soil-pH$_{(H_2O)}$ 5.5 to 6.0.

3. Root growth in the unlimed soils is severely restricted to the upper 5 cm soil layer. Those which are able to penetrate to the unlimed subsurface layer exhibit typical Al-toxicity symptoms: severe stunting and thickening of roots, and suppression of lateral roots, resulting in a knobby appearance.

4. There seems to be no substantial Ca movement into the unlimed subsurface soils during the 45 day growing period.

5. The importance of deep placement of lime is clearly indicated. Therefore, whenever possible, lime incorporation to 30 cm is strongly recommended to reduce the barrier function of aluminum to root growth in the subsurface soil

Corollary to the four mentioned objectives was the need to look into lime effect on corn grain yields under natural environmental condition. To accomplish this, field experiments were conducted on a Latosol from Darmaga and a Podzolic soil from Jonggol. On the Latosol from Darmaga, the treatment consisted of six levels of calcitic limestone, equivalent to 0.125, 0.25, 0.50, 0.75, 1.00, and 1.25 SMP-LR-$pH_{6.0}$ test value; each plot received basal fertilizers of 100 kg N, 250 kg P, 45 kg Mg per hectare. The experimental design used was a completely randomized block with eight replications. On the Podzólic soil from Jonggol, a factorial combination of P and lime were studied. Phosphorus as the main treatment, applied at three different rates, 75, 150, and 225 kg P/Ha, respectively. Calcitic limestone was the sub-treatment, and was applied at six different rates (0.00, 0.25, 0.50, 0.75, 1.00, and 1.25 SMP-LR-$pH_{6.0}$ units). This split-plot experiment had three replicates. Each plot received basal fertilizers of 100 kg N and 150 kg K per Ha. The calcitic limestone used had 80 mesh fineness and its calcium carbonate equivalent value was 98 percent. It was broadcast and incorporated to a depth of 15 cm two weeks before planting. The basal fertilizer was applied broadcast and incorporated to a depth of 15 cm two days before planting. Three redomil-treated seeds of a high yielding corn variety H-6 were spaced 20 cm apart in the row, alter thinned to one plant per hill and 100 cm between rows or equivalent to 50 thousand population density per hectare. The corn plants were harvested 96 days after planting on the Latosol from Darmaga, and 105 days on the Podzolic soil from Jonggol.

The following summary statements can be made concerning the results.

1. Corn grain yield on the Latosol from Darmaga was significantly increased by lime application. The maximum yield was obtained with 8.10 ton calcitic limestone per hectare or equivalent to 0.75 SMP-LR-$pH_{6.0}$ unit, and higher lime increments resulted in a significant reduction in yield

2. Corn grain yield on the Podzolic soil from Jonggol was significantly increased by lime application. The maximum yield was obtained with 9.64 ton calcitic limestone per hectare or equivalent to 0.50 SMP-LR-$pH_{6.0}$ unit, and higher lime increments resulted in a significant reduction in yield.

3. The overall results on both locations show that lime application equivalent to the 0.75 SMP-LR-$pH_{6.0}$ test value should be considered as the maximum amount of lime needed to obtain optimum corn grain yield, and that liming beyond this amount is potentially detrimental.

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