Liming of Hawaiian sugar cane soils has passed through a complete cycle in the last 60 years. As an established practice in the final decade of the last century, it continued well into the present century, only to cease completely about 1925. From this period until the early 1950s, lime was not applied in any degree to sugar cane fields, even experimentally. At the time of writing, liming is again a standard practice on many of the plantations which had abandoned the operation 35 years earlier. Before seeking the underlying reasons for this anomalous liming practice, it will be in order to consider briefly the nature of the soils with which it has been associated.

The application of lime in the culture of sugar cane in Hawaii has largely been restricted to members of 3 great Soil Groups: (1) the Humic, (2) the Hydrol Humic, and (3) the Humic Ferruginous Latosols. As the term 'latosol' signifies, these soils have been derived by the laterization process, whereby the bases and silica have been removed in varying degree from the solum by leaching.

These soils are moderately acid to very acid in reaction and range in base saturation from intermediate values to as low as a few percent. Exchange capacities vary roughly between 20 and 60 m.e./100 g and at the higher levels are in large part associated with the organic fraction of the soil. The soils are semi-irrigated to unirrigated; mean annual rainfalls range from about 60 to 175 in.

Lime appears to have been employed in moderation in the earliest applications of this material to the sugar cane soils. The usual treatment appears to have been 8–10 barrels/acre in the case of quicklime, or of from 0.5–3 tons/acre with hydrated lime or limestone, the lime generally being applied by spreader and worked well into the soil prior to planting. Applications were made at intervals of 6 or 7 years, which corresponds to the usual cycle of the cane crop. Lime was sometimes applied to ratoon fields.

It seems improbable that the quantities of lime applied to these highly buffered soils would have had much effect upon the degree of acidity. Nor is there any reason to believe that the planters were under any delusions in this regard. The litmus initially employed as an indicator of soil reaction offered little indication of the quantity of lime required to achieve any predetermined degree of neutralization. In later years, the Vietch procedure for determining lime requirement was employed, but little effort appears to have been directed toward achieving a high degree of neutralization.

Many and varied were the arguments advanced in support of liming. It is not surprising in view of the advances in knowledge of soils and soil–plant relationships of the past 50 years that some of these theories are no longer tenable. The feeling...
appears to have been general that soil acidity *per se* was undesirable, not in harmony with good farming practice, and, therefore, should be corrected. In somewhat later years, undue emphasis upon the importance of soil acidity in relation to nitrification lent impetus to liming programmes. No concern appears to have been expressed that calcium as a nutrient might have been a limiting factor of growth.

Whatever the motives for liming, agreement that sugar cane benefited from the treatment appears to have been unanimous. Typical is the reply of a plantation manager more than fifty years ago to a question put to him regarding the benefit of this operation: *'I have noticed that fields that have been limed compared with those that did not receive an application, were very much better; that there was a vast difference in the appearance of the cane—the cane was green, strong and healthy compared with the fields that had not been limed...'.*

**EARLY FIELD EXPERIMENTS WITH LIME**

Efforts to place the value of lime in the production of sugar cane on a quantitative basis were made in the course of time by means of field experiments. The first test with a published record was conducted on the Island of Hawaii during the period of 1909-11. It showed modest but consistent gains in sugar with increasing amounts of coral sand up to 2 tons/acre. Whether or not the gains realized would be considered significant by present-day standards is open to question.

Within a few years, additional tests with lime were initiated in other areas. In the 20 years that followed these earliest experiments, testing with liming materials was expanded to cover practically all of the acid sugar cane soils of the Islands. The various forms of lime available for the purpose and amounts of these materials, ranging from a few hundred pounds up to 18 tons/acre, were investigated. Residual effects of lime were also studied.

The results of 25 of these experiments were reviewed by Verrett in 1924 and again in 1926. These tests were conducted during the 8-year period immediately preceding the date of the initial report. Half of these tests showed no gain whatever from lime. Slight gains were registered by the remaining half, but in no instance was the increase considered significant. Average quality ratios with and without lime were nearly identical.

In 1933, Verrett again reviewed the status of the lime experiments and included 11 tests not previously reviewed. Again there was little, if any, evidence of increased yields as a result of liming. Now, however, there were indications that juice quality was generally better where lime was not applied.

Interest in liming sugar cane soils all but vanished as the result of this overwhelming evidence that the operation was an unprofitable one. Sufficient interest remained, however, to move the Experiment Station to study further the effect of lime on juice quality. A test with this objective was conducted at the Manoa Substation and reported by Doty in 1935. As with so many of the previous experiments, no gains resulted from lime, and juices were of poorer quality on limed than on unlimed soils. Part of a subsequent study by Ayres involved liming large pots (2' x 2' x 2') of soil from the same area to pH 6.0. Under these conditions, modest increases in yield of cane were obtained from liming and juices were not adversely affected.
CALCIUM STATUS OF HUMID REGION SOILS

Ten years after Verrett's final report on the lime experiments, Ayres reported the results of a comprehensive study of many of the chemical properties of the Humic and Hydrol Humic Latosols of the island of Hawaii. It was on these soils that the most intensive liming had been practised and on which the majority of the lime experiments had been located.

This study revealed the presence of soils extremely low in exchangeable calcium, levels which have since been recognized as being indicative of extreme deficiency for sugar cane. It was shown, moreover, that reserves of calcium, as determined by fusion analysis, were also very meagre, in some instances as low as 0.10%, and that more than half of the total calcium was present in exchangeable form. Calcium saturation in some areas was found to be below 1%.

Reconciliation of the findings of this study with the results of the earlier lime experiments was difficult. With the memory of previous tests still fresh in the minds of plantation agriculturists, the work afforded little stimulation in the direction of new experiments with lime. Unfortunately, in the absence of field tests, there was no way at the time to calibrate levels of soil calcium in terms of crop response. This was to come at a later date.

Interestingly enough, evidence from the field in support of the calcium picture in these soils, as portrayed by soil analysis, came initially not from experiments with lime, but from tests comparing different forms of phosphate. In 1949, plant crops of two field experiments were harvested which showed highly significant gains of 1.6 and 1.8 tons sugar/acre in favour of superphosphate over ammonium phosphate. These differences in yield were interpreted as indicating deficiencies of calcium in the experimental areas.

Analysis of soil samples from the zero phosphate plots of these experiments for exchangeable calcium revealed levels of only 60 and 80 lb. Ca per surface acre-foot. Since an intensive fertility survey made by the Experiment Station at this time*, together with the study already referred to, showed thousands of acres of the humid-region soils to contain less than the amounts of calcium found in the soil of these experiments, a calcium problem of serious and far-reaching proportions was implied.

CURRENT FIELD TRIALS WITH LIMING MATERIALS

Plans were made immediately by the Experiment Station to reinstitute the lime testing program abandoned 20 years before; by 1951, in cooperation with the plantations, the first of a new series of tests designed to measure the effect of limestone and gypsum on the yield of sugar had been initiated. Field trials with these materials applied in the furrow to soils of known calcium content have proceeded since that time at an accelerated rate and at the time of writing, 10 years later, some 40 such experiments have been harvested. Quite unlike the earlier tests with lime, many of these have shown highly significant increases in sugar as the result of treatment. Examples of these increases are shown in the form of yield response curves in Fig. 1.

Indicated also in the chart are respective levels of exchangeable calcium initially present in the experimental areas.

The purpose of these tests was to determine the effect on yield of meeting a recognized need for calcium as a nutrient and not to measure any possible effect of decreasing soil acidity. Accordingly, where limestone was used, application rates were very moderate, rates which would have little effect on the pH of these highly buffered soils. Moreover, gypsum, which does not decrease acidity in any degree, was commonly employed as a source of calcium and found to be equally as effective as limestone. It is apparent then that the beneficial effects of these materials on yield, so evident in Fig. 1, are due only to the calcium which they contained. It may be noted here that the experimental soils are adequately supplied with available sulphur, hence any possible effect of the sulphur in gypsum may be discounted. The shape of the curves in Fig. 1 implies that, despite large gains from treatment, optimum yields were not generally achieved. It may be noted in the chart that levels of soil Ca in any instance did not exceed by very much the very low value of 200 lb./acre.

With this complete confirmation of the fact that thousands of acres of sugar-cane land in Hawaii are seriously deficient in calcium has come the urge to correct the condition as quickly and effectively as possible. This correction is being accomplished by moderate additions of ground limestone to areas shown by soil or tissue analysis to be deficient with respect to this element. Applications of limestone generally are of the order of 1000–3000 lb./acre and for the most part are broadcast and ploughed into the soil immediately prior to planting. It has not, however, been determined if this practice results in more effective use of limestone than would occur should application be localized in the cane lines. Thus after a lapse of a quarter of a century, liming of sugar cane soils is once again in vogue in Hawaii.

In view of the unquestionable gains in the yield of sugar from calcium-containing materials, evidenced in the recent series of experiments, one naturally wonders at the complete absence of corresponding increases in the earlier tests. The answer, seemingly, is a simple one and appears to be associated with the 3 following related facts:
First, until about 1925, liming had been widely practiced in the more humid sugar cane areas. With failure of the earlier group of experiments to respond to liming, this practice ceased and thereafter calcium was applied only in comparatively small amounts incidental to the use of phosphate fertilizers. This resulted in inadequate compensation for normal losses of Ca by leaching, erosion, and removal from the field at harvest.

Second, coincident with this change in the calcium economy of the soil was another change of perhaps equal importance—abandonment of the use of nitrate of soda in favour of ammonium-containing nitrogen carriers. As is well recognized, hydrogen ions formed in the conversion of ammonium to nitrate, a process which takes place within a short time following addition of the fertilizer to the soil, effectively lower the level of calcium under conditions conducive to leaching.

Third, during the past 20 years or so there has been the factor of mechanization in the harvest field in the humid areas which, as practised in Hawaii, is very destructive of soil fertility. Since in these soils levels of Ca as well as of other bases diminish with depth, the accelerated erosion brought about by mechanization has resulted in decreased levels of this element in the surface layer. Moreover, much of the Ca taken up by sugar cane is contained in non-millable portions of the crop which under mechanization are also removed from the field.

THE CRITICAL LEVEL FOR SOIL CALCIUM

The pH of tropical soils as observed in a recent publication by Venema¹ is not a satisfactory indicator of the calcium status of the soil. It is employed on Hawaiian sugar cane soils only to obtain a first approximation as to the calcium status, to differentiate between soils adequately supplied with this element and those whose status may be in doubt. Where doubt exists, the content of exchangeable calcium is determined.

For an analysis of a soil for calcium to be of practical value to the plantation agriculturist, it is necessary to know the level of soil calcium below which the addition of calcium may be expected to result in increased yields and above which it may not. An approximation to this point may be obtained from Fig. 2 where are shown the results of all available calcium experiments embracing zero calcium plots, in relation to initial levels of soil calcium. These experiments, conducted on soils ranging in calcium content from about 50 to nearly 3000 lb./acre and totalling 34 in number, are arranged from left to right in the chart in order of decreasing level of soil calcium. All indicated responses possess statistical significance.

The chart reveals consistent gains in sugar from calcium containing materials on soils with less than about 400 lb. Ca/acre. Of the 24 tests in this category, 20 gave significant increases, while the remainder gave non-significant increases of 0.4, 1.5, 1.6 and 1.7 tons sugar/acre. None of the tests on soils containing in excess of 400 lb. Ca showed a significant increase from treatment.

Although a considerable gap in the data is occasioned by the absence of experiments on soils containing between about 400 and 700 lb. Ca/acre, the critical level for significant response is tentatively taken at 400 lb. on the basis that above this amount, gains of the calibre indicated have not been achieved. Taking 400 lb. Ca/acre as the
A. S. Ayres

Critical level for significant response does not, of course, preclude the likelihood of substantial, non-significant gains at somewhat higher levels of soil calcium. For this reason and because limestone is a comparatively inexpensive material, its employment in moderate amounts is recommended even on soils enjoying a calcium status more or less above the critical level.

![Graph 1](null)

**Fig. 2.** With few exceptions significant gains in sugar have resulted from application of Ca containing materials to soils containing less than 400 lb. Ca/acre.

![Graph 2](null)

**Fig. 3.** Increases in tons sugar/acre resulting from application of calcium are inversely related to initial levels of soil calcium.

The relationship illustrated in Fig. 2 indicates whether or not additional calcium is needed. However, a simple indication of a need does not answer the question as to the magnitude of the deficiency or the amount of limestone necessary to correct it. The answer to these questions is, nevertheless, inherent in the results of the field trial, together with related soil-calcium data. This becomes apparent when levels of soil calcium in the tests represented in Fig. 2 are plotted against corresponding gains in sugar. The resulting relationship is illustrated in Fig. 3.

Here it will be seen that where the initial level of soil calcium exceeds about
1000 lb./acre, there is no suggestion of increased sugar from calcium-containing materials. As the supply of Ca drops below this level, however, gains in sugar become apparent, increasing with diminishing soil calcium and reaching impressive proportions on soils containing in the vicinity of 100 lb. of the element per acre. With the aid of this chart and knowledge of the Ca status of a particular field, an indication may readily be obtained as to the magnitude of the response that would be expected to result from the application of limestone to the particular area. The quantity of Ca required to achieve this response becomes the difference between the level of Ca in the soil and the level necessary to ensure optimum growth.

This amount of calcium is readily obtainable from Fig. 4, where is reproduced the convenient form employed in reporting soil-calcium data to the plantations. This chart which is based upon the relationship shown in Fig. 3 makes possible simple graphical presentation of the analytical data in its relation to the recommended application of calcium.

In this chart it is arbitrarily assumed that plantations will consider it economical to capitalize on all gains in sugar realizable from maintaining Ca at around 800 lb./acre. Recommendations for calcium are indicated in terms of Ca rather than limestone since, where calcium containing phosphorus carriers are used as is frequently the case, the deficit of Ca may be made up all or in part from these sources.

Since a plantation may wish to apply Ca on either a crop or a crop-cycle basis, the chart is provided with two scales for rate of application. For a single crop, the range is from 0–800 lb. while for the crop-cycle, which normally consists of three 2-year crops, it is from 0–1200 lb. The latter allows for depletion of Ca at the rate of 200 lb./acre per crop. On the basis of data at hand, a 100-ton crop of sugar cane may be expected to take up around 100 lb. Ca/acre. Although no in situ evidence is available, laboratory studies suggest that leaching losses of Ca from these soils would be expected to approximate an additional 100 lb./acre per crop. Laboratory studies, incidentally, have shown that Ca applied to these soils as gypsum is far more readily leached than when applied as limestone.

In completing the form, the Ca analyses for the particular field are indicated on
the curve by a series of accurately placed dots of appropriate diameter. Immediately adjacent to each dot, the number of the corresponding soil sample is indicated. Where some or all the samples contain in excess of 1200 lb. Ca (the highest figure shown on the ordinate) the analyses are tabulated on the chart. Upon receipt by the plantation, the manager or agriculturist has only to glance at the report to note the Ca status of the field and the recommended rate of calcium application, be it for a single crop or the entire cycle.

**EFFECT OF HEAVY LIMING ON YIELD OF SUGAR AND SOIL PROPERTIES**

Wholly apart from the question as to whether a need exists for additional calcium as a nutrient, is the question as to whether the productivity of the soil will be increased by liming in excess of the rate necessary to meet this need. In Hawaii the answer to the former question appears rather clear; the answer to the latter is still obscure.

Numerous beneficial and some detrimental effects on productivity are commonly attributed to the heavy liming of acid soils. A number of these effects are under study at the Experiment Station and the results to date may be briefly summarized as follows:

1. **Soil reaction:** Soil pH increases consistently with increasing application of limestone.
2. **Nutrient balance:** In pot studies liming even to neutrality, an operation which on one soil required 20 tons limestone per acre, produced no adverse effect on yield of millable cane. Response to limestone on these calcium-deficient soils has been restricted to the smaller applications and is attributed to the ability of limestone to meet the requirement for Ca.
3. **Solubility of Manganese:** Amounts of Mn extractable with N-NH₄OAc, pH 4.8, have been shown to decrease consistently with increasing application of limestone.
4. **Solubility of Aluminium:** The solubility of Al in N-NH₄OAc, pH 4.8, has been found to diminish with increasing rate of application of limestone.
5. **Retention of Potassium:** Partial replacement of exchangeable hydrogen by calcium through liming has repeatedly been shown to enhance the ability of the soil to retain K from KCl against leaching.
6. **Mineralization of organic Nitrogen:** Stimulation of microbial activity through heavy liming has been found to markedly increase the rate of conversion of nitrogen from organic to inorganic forms. N thus liberated as the cane crop approaches maturity, quite possibly accounts for the inferior quality of juices so frequently associated with experimental heavy liming.

**DISCUSSION**

Since reliable techniques are available for determining the Ca status of the soil, and since replicated field experiments have established rather accurately the amount of lime necessary to supply adequate quantities of Ca as a nutrient, liming research in Hawaii is now centered upon determining the impact of pH changes on sugar production. Rates of limestone as high as 23 tons/acre are being tested by a number of plantations situated in the higher rainfall areas. These experiments are similar to some of the lime tests conducted in Hawaii prior to 1930. Although most of these tests indicate no beneficial effects of high rates of liming, further basic research is being carried out...
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to clarify the problem. Such clarification should either confirm or refute, so far as Hawaiian soils are concerned, the conclusions of VENEMA who, after reviewing the results of liming in tropical areas the world over, concludes, "Liming acid tropical and sub-tropical soils will only be applicable where calcium as a plant nutrient has become a limiting factor in plant growth.'

SUMMARY

The history of liming acid sugar cane soils in Hawaii from the inception of the practice to the present time is reviewed. Field experiments and related soil analyses have shown that thousands of acres of humid region cane land are deficient in calcium as a nutrient. A relationship between soil calcium and increases in tons of sugar per acre resulting from the addition of Ca-containing materials is presented. From this relationship and the analysis of a given soil for Ca, one can readily determine whether or not a need for Ca exists, the degree of response to be expected from an application of Ca, and the appropriate quantity of Ca to apply.

REFERENCES


DISCUSSIONS

I. J. P. COIGNET (S. Africa): I would like to quote our experience in South Africa where in the 'maize triangle' failure of crops occurred in spite of adequate application of N, P, & K. Trace elements and calcium carbonate experiments were carried out and it was found that Mo was the key element. The addition of Mo to fertilizers brought back the fertility of these fields. The addition of CaCO₃ also enhanced the availability of Mo.

L. D. BAYER (Hawaii): Spectrographic analysis of plant tissue showed no deficiency of Mo. H. EVANS (B. Guiana): These problems were also experienced in British Guiana some ten years ago. Very high responses to CaCO₃ application were observed on soils with high exchangeable Ca. These responses are believed to be the result of an increased P availability. In Demerara, where increased calcium was low, applications of CaCO₃ increased cane tonnage, corrected Mo deficiency and reduced Mn toxicity. In very toxic aluminium soils (Cat clays) where there is a layer of sulphides and sulphates of Al and Fe, 18" below the surface, the aluminium was removed by flooding the soil with sea water. Cat clays thus treated grow quite normal crops. Toxicity of Aluminium was observed when exchangeable aluminium exceeds 60% of the total exchangeable bases. When exchangeable Ca is increased to more than 40% of T.E.B. the soluble Al recedes into the clay.

D. S. HUGHAN (S. Rhodesia): (1) Is it necessary to add magnesium limestone as a balance to CaCO₃? In Southern Rhodesia they add one part dolomite to 2 parts agricultural lime. (2) Have any adverse effects been found when adding excess lime?

H. P. CLEMENTS (Hawaii): Calcium was added in the form of carbonate but not as oxides. CaO may cause severe chlorosis when applied in furrow prior to planting.

P. HALAIS (Mauritius): The critical level to calcium fertilization has been raised recently to a soil content of 1200 lb. of exchangeable calcium per acre. In such cases is the limit of 0.06 Ca% dry matter of the 8-10 internode tissue previously recommended, too low? Could Dr. Baver give us the latest recommendations of the H.S.P.A. in this connection?
DR. BAVER: We still consider the critical limit to be 400 lb. Ca. The 1200 figure only showed the amount of available Ca in the soil below which there might be a response.

DR. CLEMENTS: Levels of 800 and 1200 lb. are too high if Ca is considered as a nutrient.

DR. EVANS: CO₂ has not been found to be a limiting factor in sugar cane photosynthesis. Concerning toxicity, I think that iron should not be left out of the toxic elements. With regards to copper, I would consider 30–35 ppm of Cu in leaf lamina as extremely high and possibly toxic. A normal content should be between 4 and 10 ppm.

DR. CLEMENTS: The trouble with iron is that it may be precipitated at the nodes and block the vessels.

C. MONGELARD (Mauritius): In Russia, an increase of 5% sucrose yield in sugar beet has been obtained on applying carbonates to soil and this was attributed to an increase of photosynthesis, due to CO₂ increase in surrounding air and probably in the tissues.

DR. EVANS: CO₂ has not been found to be a limiting factor in sugar cane photosynthesis. Concerning toxicity, I think that iron should not be left out of the toxic elements. With regards to copper, I would consider 30–35 ppm of Cu in leaf lamina as extremely high and possibly toxic. A normal content should be between 4 and 10 ppm.

DR. CLEMENTS: The trouble with iron is that it may be precipitated at the nodes and block the vessels.

Mn, if fed into the plants as a pure culture solution would not cause trouble. Each of the toxic elements by themselves would not be serious but when combined together serious toxic effects arise.

Copper levels established in Hawaii normally run from 10 to 14 ppm.

O. D'HOTMAN DE VILLIERS (S. Africa): What is the mechanism by which the plant has drawn from the soil the extra amount of nitrogen corresponding to extra yield on plots with 34,000 lb. of CaCO₃ as compared with the zero level plots.

DR. CLEMENTS: In both of these cases there were adequate supplies of nitrogen and potassium and both were applied at higher rates than the normal practice. Nitrogen, for example, was applied at different times 6 weeks to 12 months due to leaching of nitrates. If the high level plots were more vigorous than the zero plots they would absorb more of their nitrogen and use it.

R. BAX (Mauritius): Do all varieties respond to the same extent to applications of minor elements and even to P₂O₅?

I have noticed that contents of P₂O₅ in the juice of different varieties vary greatly.

DR. CLEMENTS: When moisture regime is taken into account the variations between varieties are eliminated. Some varieties growing in phosphate deficient soils get the phosphate they need due to greater abilities of extraction whereas other varieties need additional application of that fertilizer to get the same amount of phosphate.

THE RESPONSE OF SUGAR CANE TO FERTILIZERS ON AN ORGANIC SOIL

F. GONZALEZ-VELEZ and G. SAMUELS

Agricultural Experiment Station, University of Puerto Rico
(Presented by Mr. H. K. Stender)

INTRODUCTION

The land area of Puerto Rico is about 2,165,000 acres of which 1,663,000 acres are available for farming. Organic soils, i.e. soils with over 15% organic matter, constitute less than 2% of this area. The majority of the organic soils are untilled because of very poor natural drainage, complicated sometimes by the presence of harmful salts in the profile; when properly drained and managed however, these lands can rank among the most productive soils of the Island.

One area of organic soil now being reclaimed is that of Cano Tiburones at Arceibo. This land-reclamation project under the sponsorship of the Land Authority of Puerto Rico has so far made available approx. 6,000 acres of a Tiburones muck for agricultural use. The Land Authority began growing sugar cane on this reclaimed land but sugar yields were not satisfactory despite the applications of high rates of 9/14–4–10 fertilizer used with success on mineral sugar cane soils nearby.