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Soil Toxicities as Causes of Sugarcane Leaf Freckle, Macadamia Leaf Chlorosis (Keaau), and Maui Sugarcane Growth Failure

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ERRATUM

SOIL TOXICITIES AS CAUSES OF SUGARCANE LEAF FRECKLE, MACADAMIA LEAF CHLOROSIS (KEAAU), AND MAUI SUGARCANE GROWTH FAILURE

Page 7, line 1:	Read per pound of ammonium nitrogen instead of per pound, ammonium nitrogen.
Page 18, line 15:	Read buffer curve instead of buffer curse.
line 24:	Read adsorbed instead of absorbed.
Page 31, line 4:	Read V–$Ca(NO_3)_2$, CaP; instead of V–$Ca(NO_3)_2$mCaP.
Page 37:	Add superscript ^{2} after center head MAUI SUGARCANE GROWTH FAILURE.
Page 40, line 13:	Read bucket instead of basket.
line 32:	Delete parentheses around SA and DAP.
line 34:	Delete parentheses around CaP.

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INTRODUCTION

Yields of sugarcane receiving adequate mineral nutrition may be predicted by equations involving only sunlight, maximum temperature, minimum temperature, age of the cane, and tissue moisture levels for the period of calculation (7). Except for the nutrients and water added to them, intensively cropped soils, other than serving as reservoirs, contribute little of a positive nature to crop yield and often have negative effects. The most ideal soil would be one which detracts in no way from the yield potential of the particular site. Such a soil probably does not exist. Many biotic factors in the soil probably are dominant causes of reduced yields as well as of permanent varietal decline, even though other biotic factors are helpful. Lack of adequate soil oxygen is probably as important a factor as lack of any nutrient or water. Solutes which exist in the soil solution may be helpful as well as harmful. In very acid clay soils, many essential minor elements are as frequently toxic as they are helpful.

Some nonessential elements resulting from natural weathering can be very toxic. Often quantities of such elements are increased in the solution by the fertilization practices. Although this bulletin will concern itself only with the inorganic toxicities, many of the organic solutes, including the entire array of degradation products resulting from the various decay cycles of biological remnants, are toxic, although some are stimulative (*31, 32, 33, 34*).

STATEMENT OF OBJECTIVES

The natural compositions of some of Hawaii's crop soils derived from lavas are explored to determine the toxicities caused by inorganic solutes, their origin and nature, their effects on certain crops, and methods of correction. Particular attention is directed to three very severe maladies which occur in soils commonly found in Hawaii: leaf freckle of sugarcane, macadamia leaf chlorosis, and Maui sugarcane growth failure.

COMPOSITION OF VARIOUS LAVAS

Since most of the soils in Hawaii are derived directly or indirectly from volcanic lavas, their composition is cogent at this point. Macdonald (*12*) reports the major elemental composition of several lavas (Table 1). There is an overall similarity, although variations among them undoubtedly help to explain differences crops contend with in various fields. Silica in the form of silicates is the dominant constituent. Other elements are aluminum (as Al_2O_3), ranging from 9.1 to 19.8 percent, ferric iron (as Fe_2O_3), from 2.6 to 9.1 percent, and ferrous iron (as FeO), from 1.0 to 10.4 percent. The ordinary bases, Ca, Mg, K, and Na as oxides, make up anywhere from 5.9 to 36.7 percent of the several lavas. Manganese oxide, ranging from 0.13 to 0.24 percent, is very low considering its importance in some acid soils. Titanium oxide makes up 1.1 to 4.3 percent, and phosphorus pentoxide (P_2O_5) from 0.2 to 2.4 percent.

Table 1. Percentage composition of several lavas (after Macdonald [*12*])

	Volcanic areas				
Oxides	Waianae	West Maui and Molokai	Mauna Kea and Kohala	Hualalai	Koloa
SiO_2	45.9 -49.8	45.2 -58.0	45.5 -51.8	45.6 -46.8	40.0 -45.4
Al_2O_3	13.5 -17.3	13.3 -19.8	14.0 -17.1	13.9 -15.3	9.1 -16.4
Fe_2O_3	4.2 - 9.1	2.6 - 7.0	3.1 - 6.4	3.1 - 4.6	3.0 - 7.0
FeO	4.1 - 9.7	1.0 -10.4	6.3 -10.1	8.1 -10.2	6.2 - 9.7
MgO	3.6 - 5.3	1.0 - 6.5	2.4 -16.3	7.1 -10.0	4.3 -15.9
CaO	6.4 - 9.4	1.7 -10.3	5.0 -11.8	9.6 -11.5	8.6 -14.3
Na_2O	3.0 - 4.6	2.8 - 6.2	1.5 - 5.8	2.4 - 3.2	2.1 - 5.3
K_2O	1.1 - 2.1	.4 - 3.0	.3 - 2.8	.9 - 1.1	.5 - 2.0
H_2O+	.33- .92	.2 - 2.1	.2 - .8	.2 - .6	.2 - 1.0
H_2O-	.54- .96	.4 - 2.4	.2 - .7	.1 - .2	.4 - 1.1
TiO_2	3.0 - 4.3	1.1 - 3.7	1.4 - 4.0	2.1 - 2.6	2.0 - 3.2
P_2O_5	.2 - 1.1	.6 - 2.4	.3 - 2.0	.2 - .4	.4 - 1.7
MnO	.13- .18	.15- .24	.16- .22	.16- .18	.15- .19

HISTORY

McGeorge (*19*), as early as 1925, recognized the dangers to cane growth from salts of aluminum and manganese and noted that lime seemed to have little effect on them but found that phosphates gave temporary correction. Although he did little work with iron, he noted that ferric iron would be harmless under existing conditions but warned that ferrous iron "may be associated with the infertility of some of our poorly aerated, highly organic soils." He had noted earlier (*16, 17, 18*) that soluble "crystalloid" salts of iron, aluminum, and manganese were found where the soil pH was below 5.8, that manganese was not in the soil solution at pH 6.0 or above, and that iron and aluminum at such pH's existed as the hydrosols of ferric aluminum hydrates. He also recognized the possibilities of aluminum and manganese being associated with root rots but pointed out that the soils involved were very low in phosphorus. In these papers he recognized iron compounds but generally seemed to underestimate their importance.

Essentially nothing was added to this area of knowledge in Hawaii for the next 35 years. In 1951, the plantations of C. Brewer and Company began intensive field experimentation with coral stone and phosphorus (P). Amounts of P_2O_5 were 0, 200, and 400 pounds per acre from treble superphosphate. Finely ground coral stone was applied at 4 levels, beginning with 0 and ending with the amount needed to bring the pH to 7.0, as determined from buffer curves developed by Matsusaka and Sherman (*15*). As a result, the highest amounts in each experiment ranged from 11 tons/acre at Hilo to 17 tons/acre at Pepeekeo and 23 tons/acre at Paauhau. In 1961, Clements (*2*) reported on a large number of experiments dealing with high-level applications of coral stone, which showed that the improvement in growth of cane was due to effects of calcium (Ca) other than nutritional. When the pH was well below 5.6, where there was soluble aluminum (Al) and iron (Fe) in the soil and where the manganese (Mn) index of sugarcane was above 100 ppm, there was a strong response to carbonate, the effect of which was to reduce the amounts of these absorbed by the plant. In addition to enhancement of the Ca content of the plant, the P level was also increased due to the improvement of the root environment brought about by the elimination of the toxic materials.

In 1961, Rixon (*27*) wrote a thesis on studies he made on the soils from some of these experiments and noted that, in general, the highest amount of coral stone applied did not raise the pH to 7.0; that there was a marked increase in exchangeable Ca, generally from less than 1 meq/100 g to as much as 38.82; that the extractable Al was reduced although not very sharply; and that even the highest amounts of coral stone did not affect the cation exchange capacity of any of the soils.

In 1961, Suehisa (*30*) reported a study of the effects of various phosphates and various forms of silicates on the composition and yield of sudangrass grown on three distinct soil types: Aluminous Ferruginous, Low Humic, and Humic Latosols. Only in the latter was there a marked increase in yield attributable to the silicates, hence he concluded that the use of silicates for increasing P availability may be limited. He noted, however, that soluble silicates had very pronounced effects on reducing extractable Al.

In 1962, Monteith (*20*) wrote a thesis comparing the effects of calcium carbonate with calcium metasilicate on the growth of sudangrass on a Ferruginous (Puhi) and a Hydrol Humic Latosol (Akaka). He obtained increases in yield for both in the latter soil, but only for the silicate in the former.

As a result of these studies, G. D. Sherman (*20*) planned a field experiment using TVA slag and phosphate at Puhi, and the senior author (*3, 4*) planned one with sodium silicate, coral stone, and superphosphate at Kilauea, both being in low-productivity soil areas on Kauai, and both experiments were installed in 1960. The Puhi experiment showed excellent yield responses to the TVA slag. The

Kilauea experiment showed a significant decrease for coral stone, no response to phosphate, and a significant increase for the sodium silicate. There followed numerous field experiments using either TVA slag or the considerably better pseudowollastonite ($CaSiO_3$), developed as a result of cooperative efforts by the senior author and officials of the Hawaiian Cement Company. Efforts to explain the increased yields resulting from the silicate usually stressed decreased Al and increased P and Ca. In 1967, Clements, Putman, and Wilson (*6*) published their findings on studies involving the very toxic soil at Kilauea, Kauai, and demonstrated clearly for the first time that ferrous iron (Fe^{++}) was by far the most dominant constituent of the soil solution, causing reduced root growth, reduced yield, and a leaf freckling.

Other work includes that by Mahilum (*13*) on the coral stone experimental plot soils. His thesis verified the finding reported above relating to the lowering of the Al levels by lime and also pointed to the readiness of leaching of Ca. He observed particles of coral stone still remaining after several years and showed that, by raising the temperature of the soil, these disappeared and the pH rose to the anticipated level.

Fox (*8*) and his associates published data showing the distribution of silicon (Si) within the cane plant and also the seasonal variation in the absorption of silica (SiO_2). They emphasized the importance and activity of soluble Si.

Elsewhere, Halais and Parish (*10*), in Mauritius, made use of the manganese:silica ratios in diagnosing silicate needs of cane. Even though Mn seems less important than other elements on potentially troublesome soils, a high ratio warns of toxic conditions. Thus, Halais (*9*) has also been able with the use of silicates to regenerate senile soils where Fe has been a dominant factor.

Samuels and Alexander (*28*), in Puerto Rico, have confirmed results obtained in Hawaii and are extending their research to include any possible roles Si may have in sugarcane physiology, particularly in the various enzyme systems, including those associated with photosynthesis and storage of sucrose.

Fundamental research continues in Japan on the role of Si in rice, begun in 1936 by Okawa (*23*). The effect of silicate on the structure of the rice plant and its resistance to insect and fungus attacks implies that Si, though not an essential element in the botanical sense, is a valuable agronomic material and the cheapest available to accomplish the purposes discussed.

A better understanding of the Fe complexes in soils results from the recent review by Oades (*22*). Organic materials have a marked effect on the formation of Fe^{++} in soils having various redox potentials. Motomura (*21*) shows that a soil may be quite toxic under one set of conditions and not under others, as is the experience in sugarcane fields in Hawaii. The fundamental approach being made at the International Rice Research Institute (*26*) to portray the multiplicity of changes occurring in soils as they become flooded or drained has application far beyond the rice paddy.

It has long been recognized that ammoniacal fertilizers leave acid residues. Thus, Pierre (*24, 25*) reported that the acidity which 1 ton of ammonium sulfate (21.1 percent N) adds to the soil requires 2249 pounds of calcium carbonate for neutralization, one ton of ammonium chloride (26.1 percent N) 2786 pounds, etc.

Kanehiro and Hadano, (*11*) reported that, per pound, ammonium nitrogen, ammonium sulfate, ammonium nitrate, mono-ammonium phosphate, and diammonium phosphate all have about the same effect on soil acidity. These forms of nitrogen are commonly in use because of lower cost, but rarely does one find in Hawaii a sustained program of adding neutralizing agents. Samuels and Gonzales (*29*) more recently showed the long-range effect of continued use of sulfate of ammonia to be a very serious accumulation of soil acids.

SUGARCANE LEAF FRECKLE

The term "leaf freckle" has been applied to maladies of more than one origin. As used in this bulletin, it applies to a condition which manifests itself on sugarcane growing on acid soils, particularly following the winter period (Fig. 1 and 2). It has been especially severe on poorly drained Aluminous Ferruginous, Humic, and Hydrol Humic Latosols following cold periods of heavy rainfall. Fields of plant cane planted during the March to July period generally develop vigorously, and by December the crop appears to be growing extremely well. As the rains increase and the temperature drops, however, growth slows down and the leaves, including the spindle leaf, begin to show small elongate spots (Fig. 2*a*) which fail to develop chlorophyll and hence appear as yellowish areas. As the leaf ages, the spots become reddish (Fig. 2*b* and *c*), then brown, and finally dark gray brown and necrotic. In the meantime, the spots enlarge, previously green areas lose their chlorophyll, and the necrosis spreads (Fig. 1*b*). Frequently, mirrorlike, silvery spots develop on the distal surfaces, particularly those exposed to full sunlight. During the time when the spots are reddish, the field may have a bronze cast (Fig. 1*a*), and later, as necrosis spreads, the older leaves die prematurely. In contrast to healthy plants, which may have 10 to 14 living leaves, affected plants may have only 7 or 8, but even these leaves are developing freckles and hence are considerably less than fully efficient.

Because of the freckles and the cold weather, growth slows down considerably. Even when spring comes, growth does not resume as it normally should, and what once seemed like a fine crop takes on an appearance of openness with small cane tops and slender upper stalks. Often weeds begin to grow, and at harvest the canes are light in weight and the yields very disappointing.

Soil conditions associated with this development include poor drainage and low pH, usually in the range of 4.0 to 5.0. Profiles of the soil almost always show occasional dark masses which smell of hydrogen sulfide.

Experimental Background

The first convincing demonstration of the correction of freckling resulted from field experiments at Kilauea and Puhi, both on the Island of Kauai, following the use of TVA slag on the Aluminous Ferruginous Latosol. Later, similarly striking demonstrations occurred on the very acid upper fields at Paauhau, Island of Hawaii, following the use of a relatively pure calcium metasilicate. Whereas the TVA slag was shown to be an amorphous gehlenite ($Ca_2Al_2SiO_7$) with some calcium metasilicate and residual phosphate, the new product is a high-quality, crystalline pseudowollastonite ($CaSiO_3$) with some rankinite ($Ca_3Si_2O_7$) included. Similar demonstrations were seen on the upper, poorly drained Hydrol Humic Latosols at

Fig. 1. Sugarcane leaves showing bronzing and freckling. Top (*a*) shows the reddish bronzing of old leaves as well as the freckling of young ones (H53-263). The dark green leaf was detached from the stalk and inserted for contrast. Bottom (*b*) shows, from left to right, various stages of leaf freckling with two normal leaves inserted for contrast (H51-2279).

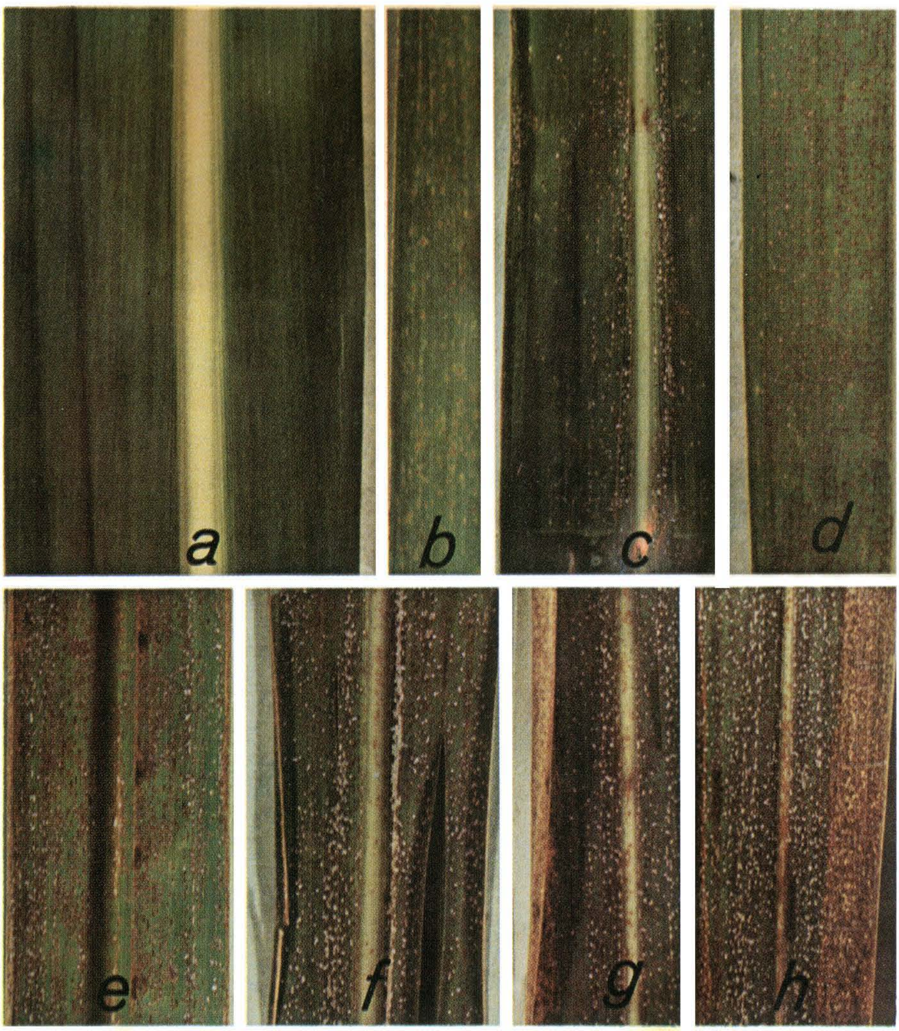

Fig. 2. Sugarcane leaves showing increasing intensity of freckling from *a* through *h* (H53-263). Lower left and lower right (e and h) show leaf underside. Lower center (*f* and *g*) shows views of upperside of leaf.

Table 2. Growth and silica analysis of sudangrass on various silicate minerals

Mineral	Predominant chemical	Silica—percent dry weight (tons of material per acre)				Dry matter—grams per pot (tons of material per acre)			
		0	2	4	8	0	2	4	8
Pseudowollastonite	$CaSiO_3$	.28	2.19	5.13	6.40	10.1	36.2	31.4	19.6
Rankinite	$Ca_3Si_2O_7$	.28	2.31	4.21	4.56	10.1	41.5	48.5	36.0
Larnite	Ca_2SiO_4	.28	3.16	2.94	5.75	10.1	32.0	44.5	19.1
Anorthite	$CaAl_2Si_2O_8$	.28	0.40	0.80	0.83	10.1	28.4	19.1	20.5
Gehlenite	$Ca_2Al_2SiO_7$	.28	1.38	2.32	2.60	10.1	36.8	20.8	32.8
TVA slag[a] (amorphous)	$Ca_2Al_2SiO_7$	.28	1.45	1.85	2.08	10.1	38.9	42.6	42.4
TVA slag[b] (crystalline)	$Ca_2Al_2SiO_7$	.28	1.48	2.51	2.76	10.1	40.1	48.5	43.6
Hawaiian Calcium Metasilicate	$CaSiO_3$	.28	2.49	3.42	3.28	10.1	45.5	44.4	46.5

[a]This TVA slag was amorphous and was determined to be gehlenite with some calcium metasilicate and also some residual phosphate.

[b]Because early in this work the amorphous nature of the TVA slag was thought to be important in its reactivity, a quantity was taken, heated to a molten state, and then cooled, producing a completely crystalline product.

Pepeekeo, Hakalau, and Onomea. Similar experiments at Pahala and Naalehu, where the Hydrol Humic Latosols are much less acid and better drained, even though cold, and where tissue silica levels are high, failed to yield any growth response to silicate. Freckling at these plantations is rarely seen. At Olokele Sugar Company and at Wailuku Sugar Company, (on the Island of Maui), where the warm Low Humic Latosols have a generally higher pH, drainage is good, and tissue silica is moderately high, no response has been noted nor is there any freckling.

Useful Silicates and Local Silicate Materials

Considerable time was given to a search for other forms of silicate which might be useful to the plantations. Small amounts of various silicate minerals, made from reagent grade chemicals by Richard Berger of the American Cement Company, were tested, using sudangrass in no. 10 cans and the known toxic soil from Kilauea. The data (*6*) are in Table 2 and should be regarded as only partially quantitative because the degree of fineness of the minerals varied, although all were very fine.

That several calcium silicate minerals might be used is evident. Anorthite, considered to be $CaAl_2Si_2O_8$, is relatively unavailable to the plant and had least effect on the growth of sudangrass. Yet gehlenite, considered to be $Ca_2Al_2SiO_7$, was considerably more available and did improve growth relatively well. In general, the calcium silicates provided more readily available silica and also improved growth the most. The amorphous nature of TVA slag is not essential.

Various local materials were similarly tested and several were quite good. Some of these data are summarized in Table 3. Kahili rock came from Crater Hill quarry near Kilauea, Kauai, and is a soft rock used for plantation road surfacing. Boulders are spread over the road and heavy bulldozers go back and forth over them, crushing and compacting them into a smooth road surface. Prior to the recent work, at least two of the plantation managers noted an apparent improvement in the appearance of the cane near the road. The trachyte rocks came from the Island of Oahu, the volcanite from Puuwaawaa on the Island of Hawaii. With each of these, there was some growth improvement, although none compared with the

Table 3. Silica content (percent SiO_2) of sudangrass grown on soil mixed with various materials

	Tons of material per acre				
Material	0	2	4	8	16
Kahili rock	.34	.68	.89	1.62	–
Kahili rock + 40% cement	.34	.94	1.45	2.01	2.32
Trachyte + 40% cement	.34	1.10	1.69	2.04	3.93
Volcanite + 40% cement	.34	.75	1.26	1.89	2.53
Cement	.34	1.47	1.53	3.67	2.69
TVA slag	.34	1.45	1.85	2.08	2.82
Hawaiian Calcium Metasilicate	.34	2.49	3.42	3.28	4.25

Hawaiian Calcium Metasilicate. Ordinary building cement by itself gave some good results but, because of its high CaO content, chlorosis and leaf burn often resulted. A red cinder from the Island of Molokai and blue basalt from Oahu, when very finely ground, gave some small improvement although not consistently.

Thus, there are several materials which might be used. Where these were used in trials for correction of freckling, sugarcane showed improved growth but this never compared well with sugarcane treated with the calcium metasilicate (made by the Hawaiian Cement Company) nor were the benefits as long lasting. Their product, currently in use as a uniformly ground powder, about 200 mesh, is prepared by burning a mixture of high-quality local coral stone and imported silica sand.

The Causes of Freckling in Sugarcane

The next problem needing clarification is the determination of the cause or causes of freckling and poor growth. Several avenues were followed: analysis of affected vs. normal leaves, root analysis, soil culture studies, and soil extract analysis.

Analysis of Cane Leaves

Kilauea Plantation Company installed a complicated experiment in one of its worst freckling fields and used 3 varieties, TVA slag ground to −16 and −60 mesh, and applied at 3 and 6 tons, respectively, and Molokai cinder ground to −180 mesh, each applied broadcast and worked into the soil vs. application under the seed at planting. The experiment demonstrated clearly that the cinder was not effective, that broadcasting and incorporating the slag into the soil with a rotovator was very effective, that placing it under the seed essentially nullified its influence, that the finer the slag was ground the greater was its effectiveness, and that the larger amount was clearly superior to the smaller amount which, in turn, was superior to the check.

Because the experiment involved 96 plots and because so many answers were already very evident long before harvest, the plantation decided to harvest only selected plots for experimental data. Regular crop log samples were taken from the ratoon which followed the harvested plots. In addition to the regular index tissues, samples were taken from the young blades (3, 4, 5, and 6) and the old blades (7, 8, 9, etc.). These were divided into bottom, middle, and top thirds and analyzed. The resulting data were put through computers programmed for multiple stepwise regression. The results for H39-7028 only are reported in Table 4, which lists the simple correlations between the particular element in top, middle, and bottom portions of young leaves (3, 4, 5, 6) and of old leaves (7, 8, 9, etc.) with tons pol/acre. In general, Ca and SiO_2 are always positively correlated with yield, while Fe, Al, Mn, Co, and Ti are negatively correlated. Since the freckling is inversely related to yield, it is reasonable to conclude that both the accumulation of Fe, Al, Mn, etc., and the low levels of Ca and SiO_2 in the leaves are the associated factors. The column headed R^2 represents the sum of the products of the correlations and the standard partial regressions, which are very high. With 95 to 99 percent of the variability accounted for, the factors listed include at least the most troublesome ones. The column at the right indicates the order of importance as determined by

Table 4. Correlations between the ash components of the leaves and tons pol/acre yields (H39-7028) (r = .765 for 1%, .632 for 5%)

Leaf portion		Ca	SiO_2	Co	Fe	Mn	Al	Ti	R^2	Stepwise order
Young leaves	Top	.794	.842	-.202	-.260	-.261	-.359	-.0327	.9878**	SiO_2, Fe, Ca, Co, Ti
3,4,5,6	Middle	.766	.926	-.330	-.328	-.339	-.583	.271	.9932**	SiO_2, Fe, Ti
	Bottom	.697	.939	-.590	-.307	-.480	-.555	-.170	.9904**	SiO_2, Fe, Ca, Al
Old leaves	Top	.807	.927	—	-.755	-.257	-.756	—	.9710**	SiO_2, Fe, Al
7,8,9, etc.	Middle	.854	.847	.287	-.285	-.349	-.604	-.065	.9478**	Ca, SiO_2
	Bottom	.904	.930	+.011	-.548	-.583	-.574	-.364	.9695**	SiO_2, Co, Ca

the stepwise regression. After completing the entire run for a particular set of data, the computer printed out the most important of the 7 X's used first, then the second, and so on, until no further significant improvement in the R^2 was obtainable. Thus, it can be seen that the dominant factors are the actual SiO_2 content of the leaves, a positive factor, and the Fe content of the leaves, the dominant negative factor.

The second variety (H53-263) used in this study showed quite similar results, with SiO_2 being the dominant factor in each case and Fe, Al, and B being the second or third in each case. Ca appeared only once and this as a third factor. The third variety (H51-2279), however, was quite different (Table 5). Although in general the R^2's are of the same order and sign, they are much lower and the stepwise order is very different. Where H39-7028 showed SiO_2 to be the dominant factor in five of six runs, and where H53-263 showed it to be dominant in all six runs, H51-2279 shows it only once as the first factor and once as a second. There seems little order to the results. This is especially pertinent since this variety has frequently given disappointing results in fields where silicate has been applied. Perhaps one reason for this is that H51-2279 seems less able to absorb SiO_2 than the other two. Untreated plots for the 3 varieties show 0.52 percent for H39-7028, 0.25 percent for H53-263, and 0.24 percent for H51-2279. The treated plots for the same varieties show 1.41, 1.37, and 1.10, respectively. The higher level for H39-7028 perhaps accounts, in part at least, for its having been a standard in the toxic soil area prior to the silicate era.

When the actual leaf composition values are displayed in Table 6, the comparisons for Fe do not seem to be very striking. Ca and SiO_2 levels are markedly different, however, and Mn also is markedly lower in the treated plots, although the actual levels even for the checks are not very high when compared with other areas. Al also is lowered by treatment, even though the levels are not very high compared with levels found elsewhere. Thus, it is possible that, once the Mn, Fe, and Al get into the leaves, if they do not encounter certain minimum levels of SiO_2 and/or Ca, they localize in such concentration that they cause necrosis. Yet, the same levels of these toxic materials are prevented from localizing by the presence of SiO_2 and/or Ca, as Williams and Vlamis (*35*) have noted for Mn in barley leaves.

An alternate interpretation is that the Fe, Al, Mn, etc., in the soil solution become very toxic to the roots, and that this is the primary cause for the yield decline, with freckling an inevitable consequence, compounding the difficulties for the plants. Many studies along these lines were undertaken in an attempt to associate composition with the toxicity shown by freckling. A new sampling of the top thirds of old leaves taken from the same field as reported above was made from check plots (X) as well as the 6 tons of 60-mesh slag-treated plots (D). These were thoroughly washed and, to avoid contamination in grinding, were cut into pieces about 1 inch square and ashed without grinding. The ash was taken up completely and analyzed by atomic absorption. To add more relative meaning to the search, similar samples of deep-green leaves showing no trace of freckling were taken from complete nutrient cultures being grown in silica sand (Z). These data are shown in Table 7. Comparing the freckled leaves from plots X with the slag-treated leaves from plots D, there was more lead (Pb), Zn, Al, Fe, and Mn than in the leaves from

Table 5. Correlations between the ash components of the leaves and tons pol/acre yields (H51-2279) (r = .765 for 1%, .632 for 5%)

Leaf portion		Ca	SiO_2	B	Fe	Mn	Al	R^2	Stepwise order
Young leaves 3,4,5,6	Top	.648	.633	-.255	-.208	-.606	-.302	.937**	Ca, Al, Fe
	Middle	.527	.534	-.504	-.243	-.321	-.116	.827	SiO_2, B, Ca
	Bottom	.648	.575	-.119	-.676	-.514	-.281	.954**	Fe, Ca
Old leaves 7,8,9, etc.	Top	.738	.600	-.522	-.071	-.546	-.228	.732	Ca, SiO_2
	Middle	.800	.658	-.466	-.420	-.592	-.370	.900**	Ca, Fe
	Bottom	.702	.595	-.555	-.431	-.738	-.406	.624	Mn, B

Table 6. Effect of TVA slag on yield and on composition of cane leaves of the three varieties

Variety		Tons pol/acre	Ca	SiO_2	Mg	Co	Fe	Mn	Al	Ti	Zn	Mo	B
H39-7028	Treated	18.4	.621	1.42	1.1	.6	142	85	50	9	28	.183	11.9
	Checks	13.9	.451	.52	.9	1.6	136	128	56	6	36	.180	13.3
H53-263	Treated	18.1	.485	1.40	1.8	1.1	116	82	46	7	23	.209	14.4
	Checks	15.2	.276	.25	.7	.7	125	126	60	5	28	.225	21.2
H51-2279	Treated	18.2	.492	1.17	.6	4.3	126	88	60	9	27	.204	13.9
	Checks	15.5	.286	.24	.6	.3	155	150	90	10	23	.193	16.8

Table 7. Composition of top thirds of leaves (ppm) from severely freckled, silicate-treated, and nutrient culture plants (H53-263)

Element or compound	Source of material		
	Freckled (X)	Silicate-treated (D)	Nutrient culture (Z)
Pb	4.3	2.7	1.3
Zn	4.6	3.7	4.6
Cu	.9	1.3	.9
Cr	.15	.11	.24
Al	18.0	8.0	55.0
Fe	78.2	50.8	171.0
Mn	88.2	34.8	119.0
Ca	1,850.0	6,500.0	16,500.0
SiO_2	2,300.0	65,000.0	8,600.0

plots D, but much less Ca and SiO_2. The perfectly green leaves of the nutrient culture plants, which turn a clean, uniformly light tan color when they die on the stalk, had much higher contents of the toxic elements than leaves from plots X, but very much higher Ca and SiO_2 levels. The same conclusion was reached as after Tables 5 and 6; namely, that leaves which are low in Ca and SiO_2 become more subject to the localization of the toxic elements and, even though the levels of these elements may become high, if Ca and SiO_2 are abundant, the toxic effects are not realized.

Analysis of Roots

If the toxicity exists in the soil solution, then root analysis may yield some cogent data. In Table 8, roots taken from the severely freckled field plants and thoroughly washed were compared with those taken from plants grown in a complete silica sand nutrient culture.

Roots from severely freckled plants are very much higher in Fe, Al, Mn, copper (Cu), boron (B), and Zn, and very much lower in SiO_2, Ca, S, Mg, and P. Thus, the same general pattern continues to emerge.

Soil Solution Toxicity

A soil culture series was set up in no. 10 cans, using sudangrass and a 15–15–15 garden fertilizer, which was a mixture of ammonium sulfate, diammonium phosphate, and muriate of potash. The data shown in Table 2 are typical of these runs. In this specific case, when the plant crop was harvested and the cultures fertilized again, ratoons of the silicate-treated pots generally grew very well but the checks were complete failures. Extracts of this soil were prepared to identify the toxic material. Early in this work, soil and water were mixed on the basis of 1 to 1.

Table 8. Composition of roots of severely freckled plants compared with those grown in nutrient culture (H53-263)

Element or compound	Roots from nutrient culture (Z)	Roots from freckled plants (X)
	Percent dry matter	
K	.90	3.38
P	.076	.054
Ca	.63	.044
Mg	.22	.088
S	.583	.119
SiO_2	2.00 (estimate)	.99
	Parts per million	
Mn	15.0	251.0
Zn	36.0	200.0
B	6.6	31.0
Cu	49.0	66.0
Al	150.0	1,540.0
Mo	6.7	2.28
Fe	288.0	12,406.0

Generally, the mixture was allowed to stand for as long as 2 weeks with occasional shaking. Later, a week of soaking was followed by 24 hours at 85 C in an oven. Still later, the mixture was allowed to stand for 24 hours and then was autoclaved at 15 psi for 1 hour and centrifuged until clear, thus maintaining the natural pH.

Two samples of Kilauea soil were used: one in which ratoon growth was a complete failure (used), the other was the soil as received from the field (new). First, a wheat-seed germination was run on the extract. Distilled water was used as a check. The "new" extract also was concentrated five times to imitate the amount of moisture at normal field capacity. The germination results are in Table 9.

Table 9. Toxicity assay of Kilauea soil extracts (wheat)

Extract	Percent germination	Shoot growth	Root growth
Distilled H_2O, check	100	strong	strong
"New" extract	47	poor	nil
"Used" extract	2	nil	nil
"New" concentrated five times	10	nil	nil

Two points are clear. The toxicity exists in the soil as received but is intensified following use of the 15–15–15 fertilizer mixture. It is clear that the toxicity in the field is the result of natural weathering, since soils which have never been fertilized are also toxic, but the use of ammoniacal fertilizers greatly intensifies the problem.

Scanning and Resin Exchange Columns

To identify the actual toxic agent, two procedures were followed: the first involved scanning the extract in the atomic absorption spectrophotometer; the second involved resin exchange columns and chemical methods for the separation and identification of the component materials, testing each fraction for toxicity with wheat-seed germination.

Scanning the soil extract showed the presence of many possible toxic materials: Fe, Mn, Al, Ti, Ni, Co, Cr, Pb, Cu, and Zn. The "used" extract had 220.0 ppm of Fe and 10.0 ppm Mn, while the "new," which also was toxic to wheat germination though less so, showed 20.0 and 1.85 ppm, respectively. Chemical tests showed the Fe to be mostly Fe^{++}. One analysis showed 0.33 mmole/100cc Fe^{++} and 0.07 mmole/100cc Fe^{+++}. The buffer curse of the soil extract was shown to be similar to that of Fe^{++}.

Chromatographic analysis of the extract showed considerable organic material, with amino acids making up 30 to 40 ppm of the total extract. Amino acids identified were alanine, glycine, serine, valine, threonine, aspartic acid, leucine, beta alanine, tyrosine, gamma amino butyric acid, phenyl alanine, lysine, arginine, histidine, and glutamic acid.

Ion exchange techniques were employed to obtain 4 fractions: a neutral fraction, a weak base cation fraction containing amino acids, an acidic fraction including inorganic anions and organic acids, and a strongly absorbed cation fraction. None of the first 3 fractions showed toxicities to wheat germination. The fourth fraction was eluted with 2*N* HCl, and the eluate was made alkaline with 6*N* NaOH to separate the metallic hydroxides. A copious blue-green precipitate appeared, was filtered off, washed free of alkali, dissolved in a minimal amount of dilute HNO_3, and the pH adjusted to 3.95 with KOH (the pH of the "used" soil extract). As was soon apparent from the color and instability of the resultant solution, the Fe^{++} had been oxidized to the insoluble $Fe(OH)_3$, and the solution was nontoxic to wheat germination.

When, however, the HCl in the cation eluate was removed by distillation under reduced pressure, the composition of the solution of the crystalline residue was estimated to be 0.004*M* $FeSO_4$ and 0.023*M* NH_4Cl at a pH of 3.95. When a solution of $FeSO_4$ half this strength (0.002*M*) and with 0.023*M* NH_4Cl was made up, adjusted to pH 3.95, germination was a complete failure with the swollen seeds showing the same darkening as had been noted when germination was attempted in the original soil extract. The iron sulfate used alone in another trial showed that it alone was the toxic agent. Of special interest is the fact that $Fe(OH)_2$ is soluble in weakly acidic solutions and that silicic acid is insoluble in them. Thus, at Kilauea, in its acid Aluminous Ferruginous Latosols, Fe^{++} undoubtedly is the dominant soil poison. As it is dissolved off the soil minerals, it accumulates in the soil solution and, because of poor aeration during the heavy rainfall period, remains in the ferrous form. Under summer conditions with good aeration, the same soil would be less toxic because ferrous iron would become ferric and would be precipitated.

At Kilauea, Al undoubtedly is also a part of the problem because the affected lands are potential bauxite sources. In soils at Akaka as well as Puhi, Monteith and Sherman (*20*) have shown that extractable Al is markedly reduced by both lime and silicate. Suehisa et al. (*29*) have shown striking reductions of extractable Al following treatment with either phosphate or silicate. Clements (*2, 4*) has shown a marked reduction of plant manganese and root aluminum as a result of liming with either carbonate or silicate.

Monteith and Sherman suggested also, as have others, that one of the principal roles of the silicate is to release phosphate to the crop. If there is any connection at all, it is doubtful that this is a principal function, since the same increase in plant phosphates follows calcium carbonate application. Thus, in Table 10, amplified phosphorus index (API) readings for sugarcane are reported for an "amounts of phosphate" by "amounts of coral stone" experiment and show a larger increase in plant phosphorus from coral than from phosphate.

Table 10. Plant (API) phosphorus readings for sugarcane in a phosphate X coral stone experiment (Hilo)

Tons of coral stone per acre	Pounds of P_2O_5 per acre			API[a]
	0	200	400	
0	1429	1387	1480	1428
2.0	1671	1762	1674	1701
5.5	1410	1975	2028	1803
11.0	1459	2107	1972	1853
Average	1492	1808	1792	

[a]Amplified phosphorus index.

In Table 11, API readings are shown for a silicate experiment, also at Hilo. As was the case with coral stone, calcium metasilicate gave a larger increase in phosphate uptake than did the phosphate fertilizer. One interpretation of this increase, due to either carbonate or silicate, has been that the treatment affects the anion exchange complex. It is much more likely that the increased absorption is the result of improving the root environment by precipitating toxic elements, and root growth is greatly stimulated (*see* later), resulting in a greater uptake of nutrients in general and phosphate in particular. It is also very doubtful that the increase in growth shown by Monteith and Sherman was due to the phosphate effect, since the carbonate had the same effect on phosphate uptake but not on growth. Although as will be noted for Keaau, growth improvement was effected equally, whether $CaCO_3$, $CaSiO_3$, or $MgCO_3$ was used. At Kilauea, Paauhau, Pepeekeo, etc., on lands where freckling occurred, the response to the silicate was more decisive than to the

Table 11. Plant phosphorus (API) readings in a phosphate X silicate experiment (Hilo)

Pounds of P_2O_5 per acre	Tons of calcium metasilicate per acre				API[a]
	0	2	4	6	
0	2093	3080	2720	2777	2668
400	1788	2840	3196	3348	2817
800	2819	3287	3382	3174	3190
1200	2804	3380	3674	3645	3376
Average	2376	3171	3264	3246	

[a]Amplified phosphorus index.

carbonate. Table 12 shows field yields in Akaka soils for plant as well as ratoon crops of sugarcane. In both plant and ratoon crops, the silicate outyielded the carbonate treatments.

Although the carbonate treatment in the plant crop outyielded the cinder treatment, which was without effect, in the ratoon the difference was just short of the 5 percent level. Similar results have been obtained at other plantations. Somehow, either the action of the silicate differs from that of the carbonate, or the resulting products differ in stability. If the action is one of precipitating such toxic elements as Fe^{++}, Al^{+++}, Zn^{++}, Ni^{++}, etc., it is not unlikely that the silicates of these elements are more resistant to weathering breakdown than are the carbonates.

Table 12. Tons of cane per acre—Akaka (average of treated plots)

Supplement	Plant	Ratoon
TVA slag	86	143
Olivine cinder	73	130
Coral stone	80	134
HSD	4.3	4.1

Specificity of the Silicate Action

Since it now seems clear that the action of calcium metasilicate is somewhat different from that of calcium carbonate, the question is whether some specific character of calcium metasilicate is involved. An array of anions was selected which would be somewhat comparable to silicate in the insolubility of compounds with such cations as Fe^{++}, Al^{+++}, Zn^{++}, Mn^{++}, Ti^{++}, etc. The results are summarized in

Table 13. This effort resulted in part also from an observation test in which the toxic soil was treated with very large amounts (1000 pounds per acre) of various elements including the minor elements. The response to sodium molybdate was so outstanding that it suggested that freckling was merely a symptom of a very severe molybdenum deficiency. This idea was dismissed when the data became available. The molybdate anion, like phospho-tungstate and others, including silicate, causes much the same kind of insoluble precipitate with the known possible toxic cations. These data, so far as these experiments go, also eliminate the idea that silicon is an essential element and that freckling is a silicon-deficiency symptom.

It is likely that the effectiveness of the very soluble sodium silicate is due in part to its strong alkalinity, and that the more or less insoluble calcium metasilicate is effective because, at its surface, the pH is estimated to be somewhat above 11. It is also possible that the calcium silicate which dissolves in the soil solution reacts with the soil particles which contain the toxic ferrous iron, thus insulating the plant roots from contact with it.

Table 13. Dry matter yield of sudangrass (grams per pot) (Treatment range: 0.25 to 2.0 tons per acre silicate equivalent, except for ammonium phosphomolybdate)

Material	Rating	Dry weight (average)
Hawaiian Calcium Metasilicate	1	23.4
Ammonium phosphomolybdate (2-12 tons/acre)	2	23.1
Sodium silicate	3	22.3
Ammonium phospho-tungstate	4	22.0
TVA slag	5	21.4
Sodium molybdate	6	21.3
Sodium pyrophosphate	7	20.7
Calcium carbonate	8	20.2
Sodium tellurate	9	20.2
Ammonium paramolybdate	10	19.9
Rankinite no. 2	11	19.8
Gypsum	12	19.2
Checks		18.9
Sodium arsenate	13	18.5

Effects of Calcium Silicate vs. Silicic Acid and of Fertilizers on Soil Toxicity

The soil toxicity reported for Kilauea results from natural weathering, since lands which never have been fertilized give strong responses to calcium metasilicate. However, it is also clear that ammoniacal fertilizers, because of the acid residues they leave, add to the amounts of Fe^{++}, Al, etc., in the soil solution, while at the same time the basic cations, particularly Ca, are lowered. Several factorial experiments were conducted, using the very toxic Kilauea soil with various fertilizer combinations as well as variable amounts of several supplements. One such experiment involved 5 supplements: A—calcium carbonate, F—calcium metasilicate, G—silicic acid, O—sodium silicate, and Y—calcium sulfate, at the rates of 0, 3, 6, and 9 tons per acre of equivalent calcium carbonate. Na_2SiO_3, because of its strong alkaline nature, was applied at one-fifth the calcium carbonate equivalent, and this was found to be too little.

Fertilizer combinations, all prepared to give 500 pounds per acre of N, P_2O_5, and K_2O, were as follows:

- I $(NH_4)_2SO_4$ (SA), $(NH_4)_2HPO_4$ (DAP),
- II SA, $CaHPO_4$ (CaP)
- III NH_4OH (AA), CaP
- IV Urea, CaP
- V KNO_3, tripolyphosphate (TPP), urea
- VI $Ca(NO_3)_2$, CaP

All fertilizer combinations included KCl except no. V, and all included $MgSO_4$ at the rate of 100 pounds Mg/acre.

Thus, this was a 6 X 5 X 4 experiment with two replications for a total of 240 pots. Air-dried soil weighing 470 g was weighed into plastic containers; the supplements were added and thoroughly mixed into the soil; the fertilizers were next applied either by pipette or as solids; the whole mass was then watered with deionized distilled water, covered, and allowed to incubate for 2 weeks at greenhouse temperatures—66 to 100 F. The covers were then removed, the contents allowed to dry and again thoroughly mixed and finally planted to sudangrass. Each culture was then placed in its randomly determined position. After germination, the plants were thinned to 5 per culture and watered as needed with deionized distilled water. The plants were harvested on December 17, 1969 (Table 14).

Calcium metasilicate is outstanding in its effect on toxicity elimination; sodium silicate is next, and it is very likely that the yield might have been better had more been applied. The sodium silicate ratoons were failures, and the soil pH, like that of the checks, indicated that the supplement had been exhausted. Silicic acid had an apparent negative effect on the growth of the grass, having a lower yield than the untreated checks (1.77 vs. 4.05). Urea and calcium phosphate were the best fertilizer combination; tripolyphosphate, and diammonium phosphate mixes, were poor. It is not possible to explain the very poor performance of $Ca(NO_3)_2$ and calcium phosphate. The plants were complete failures and seemed to suffer from an extreme phosphate deficiency. In the ratoon which followed, there was a complete reversal, and the no. VI fertilizer gave the highest yield. Finally, the largest amounts of the supplement gave the highest yields.

After the plant crop was harvested, and because it was not possible to remix the soil without destroying the roots, an application of urea was made to each of the cultures and a ratoon crop was grown. It was soon apparent that the cultures which had grown well in the plant crop were growing less well, pointing to nutrient deficiencies. The $Ca(NO_3)_2$, $CaHPO_4$ fertilizer combination gave outstanding growth, probably because it had overcome its earlier difficulties, whatever they

Table 14. Dry weight yields of sudangrass (grams per pot)

Supplement		Fertilizers		Amount of supplement (tons per acre)	
Calcium silicate	8.84 (c)	IV Urea, CaP	9.13 (c)	9	6.66 (b)
Sodium silicate	5.98 (b)	II SA, CaP	8.03 (c)	6	5.61 (a) (b)
Calcium sulfate	5.54 (b)	III AA, CaP	7.56 (b) (c)	3	4.52 (a) (b)
Calcium carbonate	3.92 (a) (b)	V KNO_3, TPP, urea	4.71 (a) (b)	0	4.05 (a)
Silicic acid	1.77 (a)	I SA, DAP	4.06 (a)		
		VI $Ca(NO_3)_2$, CaP	2.98 (a)		
HSD	2.61	HSD	3.24	HSD	2.17

were, and the ratoon fertilization in addition to the unused plant crop fertilizer gave it advantages over all the others.

The roots of the ratoon crop were shaken as free of soil as possible and green weights were taken. The root weights and the Ca and Si levels of the tops are shown in Table 15.

Table 15. Green weight yields of ratoon sudangrass roots (grams per pot) with Si and Ca composition of the tops

Supplement	Average weight of roots	Percent dry weight of ratoon tops	
		Si	Ca
Calcium silicate	4.09 (c)	1.55	2.06
Calcium carbonate	3.54 (c)	.38	1.70
Calcium sulfate	2.96 (b)	.30	1.53
Silicic acid	1.16 (a)	.78	.60
Checks	.90 (a)	.24	.71

Of very considerable interest are the SiO_2 levels of the ratoon tops. Unfortunately, these were not determined in the plant crop, but it is quite obvious that, while the plants were able to absorb Si from silicic acid, there was no benefit to them as reflected in growth either of tops or of roots. This demonstrates rather conclusively that $SiO_2 \cdot H_2O$ *per se* is not important in correcting the toxicity of the soil solution, but rather SiO_3 in combination with some basic cation.

In summary, freckling found on sugarcane plants growing on very acid, cold, and poorly drained Aluminous Ferruginous, Humic, and Hydrol Humic Latosols results in major part from the presence in the soil solution of ferrous iron salts, along with salts of aluminum, manganese, and zinc as well as some other metals. Root growth is strikingly reduced, resulting directly in reduced top growth. One may hypothesize that the absorption of these elements, particularly ferrous iron, results in their accumulation in localized areas of the leaves which, in the absence of adequate levels of calcium silicate, become necrotic, particularly those leaves exposed to direct sunlight. Photosynthetic activity is thereby reduced, compounding the plant's difficulties.

Finally, a warning needs to be made. Where the calcium metasilicate is piled in a field prior to spreading, excessive amounts may thus be applied at that spot, and this will result essentially in a growth failure of the cane crop to follow. The plants become very chlorotic and some show typical magnesium-deficiency symptoms. Affected soil from such an area was taken for a pot study. Urea was used as a source of nitrogen for all cultures, and KCl was added to give 200 pounds N and

300 pounds K_2O. $MgSO_4$ was added at 2 rates: 1000 pounds per acre and 100 pounds per acre. Other cultures received one of the following: $ZnSO_4$, $MnSO_4$, $CuSO_4$, $FeSO_4$, or a combination of these. Where used alone, each salt was applied at the rate of 100 pounds per acre. In combination they were applied at 20 pounds per acre. The results showed very outstanding growth for $MgSO_4$, but most of the others were complete growth failures.

Identifying Areas in Need of Calcium Metasilicate

Several criteria are available to the grower in identifying areas likely to respond to calcium metasilicate.

First: The appearance of freckling on cane leaves growing in poorly drained acid clay soils, following cold, wet periods, is a definite indication of need for $CaSiO_3$.

Second: Soil pH range from below 4.0 up to about 5.6. Any such soil, made up of iron and aluminum minerals, and poorly drained, is very likely to respond. If the soil is well drained but very acid, the plants might very well show poor growth due to low Ca. If the Ca index is below the critical level, a crop would respond to $CaSiO_3$, but would respond equally well to $CaCO_3$, which is much cheaper. Even in poorly drained areas showing freckling, where the pH is such as to require a large amount of $CaSiO_3$ to bring the pH up to 5.8, for example, 15 to 20 tons, a program over a period of years of applying annual or biennial increments of 1½ tons of $CaSiO_3$ and 1½ tons of the much cheaper $CaCO_3$ will, in time, remedy the problem at a reasonable annual cost. During later years, only the carbonate would be needed.

Third: Plant and soil analysis on acid clay soils. The positive identification of Fe^{++} is a good starting point. Potassium ferricyanide or orthophenanthroline is useful here. A high Mn/SiO_2 ratio in the plant tissues also warns of toxic situations. Either soil or plant levels of Si are likely to be only partially reliable at best. It seems quite clear that no Si in either plant or soil is needed if there are no toxic agents present in the soil solution. If the SiO_2 in the soil is silicic acid, then even high levels would be of no value. Failure to find freckling on Low Humic Latosols cannot be credited to the presence of SiO_2 in the irrigation water. Rather, under such soil conditions, Fe^{++} would not accumulate, hence freckling would not occur.

Fourth: Finally, the grower who suspects soil toxicities can easily and quickly verify his suspicions by a small pot experiment, using both $CaCO_3$ and $CaSiO_3$ as soil supplements and the fertilizer combination he ordinarily uses.

MACADAMIA LEAF CHLOROSIS AT KEAAU[1]

In contrast to the very highly weathered soil at Kilauea, the substrate at Keaau is essentially pure lava. The area chosen, actually an old aa lava flow, was covered with a relatively luxuriant jungle forest. In 1949, the vegetation was knocked down, either buried or burned, the aa leveled, and young grafted nut trees planted in holes

[1]The data and conclusions in this section were first reported to the management of the Royal Hawaiian Macadamia Nut Company, September 1968, in oral and written forms.

of about 1.5 cubic feet. Since there was no soil as it is commonly known, the young trees were set into soil taken from nearby farmland. Subsequent field management was a form of rock culture.

The substrate is made up of a thick layer (as much as 15 feet) of aa lava overlying pahoehoe lava and mixed with the accumulated organic debris resulting from ages of decomposition of biological remains. The aa lava itself consists of pieces ranging in size from relatively fine grains to large clinkerlike boulders. The cation exchange capacity measured 32.28 meq/100 g of soil, and the total base saturation was 30.9 percent, made up of 17.6 percent Ca, 10.3 percent Mg, 2.2 percent K, and 0.8 percent Na. Exchange acidity was 22.27 meq/100 g of soil. The area receives more than 100 inches of rainfall each year. Except in a few places where pahoehoe lava is near the surface, the natural drainage is good. However, because of management's desire to mechanize harvesting, the surface has been variously treated and compacted. It is thus not unlikely that anaerobiosis obtains in certain areas for at least a part of the time.

A leaf chlorosis began to develop on the oldest trees some 10 to 15 years after planting, appearing first as a yellowing of the leaves and then their premature excision. After a while some of the most severely affected trees died.

Work was begun on the specific problem in April 1968. The orchard management sent samples of soil weighing 299 pounds which had been passed through a ¼-inch screen. To provide these samples, 1694 pounds of material was collected from under selected orchard trees and from virgin forest nearby. Of this total, only 17.7 percent would pass through the screen, 82.3 percent was various sizes of rocks which were discarded.

The studies were made on the 17.7 percent fraction of soils taken from under 12 chlorotic trees, 2 normal trees, and from the original virgin forest nearby. At the start, the soil was sampled at four points around each tree. These were combined into a single-tree composite when it became obvious that no differences existed. For the large factorial experiments, the entire lot from under affected trees was composited.

Foliar Analysis Comparisons

The leaf samples sent from Keaau represented four intensities of chlorosis, from normal to severe. Data from fertilizer experiments involving healthy bearing trees were obtained from B. J. Cooil as part of experiments installed at Honomalino and at Captain Cook, South Kona, Hawaii. Data were also obtained from normal trees growing in Ka'u, Hawaii, from Masao Nakamura, manager of Hawaiian Orchards, Inc. These data are shown in Table 16. The major elements, N, P, K, and S, all show a rise in levels as chlorosis intensifies. This is a typical result where growth restriction obtains, and usually indicates that none of the accumulating nutrients is the cause of the malady.

Cu and Fe decreased as chlorosis intensified, suggesting possible involvement. Mn was very low as compared with the other orchards. The Ca level for the normal leaves was higher than for the other Keaau samples: .847, .467, .527, and .582. The small rise of Ca in the more severe stages was sometimes noted after severe stunting

Table 16. Leaf analysis from several orchards—Variety 246 (Keauhou)

Orchard	Degree of chlorosis	Percent dry matter							ppm dry matter						
		N	P	K	Ca	Mg	S	SiO_2	Mn	Zn	B	Cu	Al	Mo	Fe
Keaau	none	1.42	.096	.51	.85	.11	.10	.09	108	43	—	12	12	2.3	22
	light	1.42	.125	.70	.47	.09	.11	.06	87	32	—	6	11	1.5	15
	moderate	1.53	.151	.96	.53	.09	.14	.09	75	31	—	5	15	2.7	15
	severe	1.76	.183	.74	.58	.10	.15	.09	118	39	—	4	9	2.0	11
Honomalino	none	1.65	.192	.49	1.05	.13	—	—	192	8	—	3	—	—	30
Captain Cook	none	1.54	.113	.63	.45	.06	—	—	860	6	—	4	—	—	29
Ka'u	none	1.44	.100	.41	.58	.13	.07	.10	618	14	23	9	10	.60	223
	none	1.44	.084	.66	.67	.20	.08	.05	419	8	22	6	21	.70	—

occurred, i.e., even the element in deficiency tended to accumulate without additional growth. Fe also was low in the leaves and paralleled chlorosis, even though the Fe in the soil solution was very high. Zn at Keaau was very high and believed well in a toxicity range where Ca was not adequate. Mo was two to three times higher at Keaau.

From these data, it was possible to hypothesize that, within the leaves at least, Ca, Mn, and Fe and possibly Cu were in less than normal supply and that Zn might be in a toxic range. At this point, it might also be inferred that the major problem was a root problem because of toxic soil conditions, and that foliar deficiencies simply reflect the inability of the roots to perform metabolic absorption adequately.

Soil Studies

Soil extracts were made by taking 100 g (oven-dry equivalent) of soil and adding 200 ml of water. The virgin soil, because of its fluffiness, required 300 ml of water. The flasks were shaken occasionally over a 48-hour period, after which they were autoclaved at 15 psi for 1 hour. While still warm, the samples were centrifuged at 3,700 RCF for 30 minutes. The supernatants were not completely clear, so they were spun again, but at 32,000 RCF for 30 minutes. The extracts now were clear and were used for pH determinations, bioassay, and elemental analysis on the atomic absorption spectrophotometer.

The pH of the soil extracts from under affected trees (Table 17) varied from 4.25 to 4.95. The virgin soil extract showed 5.60 and that of the soil from the normal trees 5.92. A marked increase in soil acidity is clearly associated with the problem.

Bioassay consisted of germinating 20 wheat seeds (Genesee variety) in 10 ml of the extract in petri dishes. The dishes were placed in a warm room (92 F) and, after 72 hours with daily aeration, measurements of the longest primary root and the longest shoot were made. These data are summarized in Table 17. Although the results are variable, all of the extracts showed some depression of growth. The poor growth in the virgin extract suggests that the toxic situation already existed at the start of the orchard as a result of natural weathering. Very marked depression of growth, as in the cases of 5, 8, and 15, showed stunting very like that caused when pure Fe^{++} solutions were used. To check this point, drops of extract were put onto a spot plate, evaporated to dryness at moderate temperature, and tested with potassium ferricyanide solution. In Table 17, heavy dark-blue coloration, characteristic of ferrous-ferricyanide, was shown ranging from zero to an intense color represented by ++++.

When 10 g of soil were soaked in 30 ml of Na_3 EDTA for 17 hours, the color of the resulting extract varied from a red brown to yellow. Estimates of the amount of Fe in the extract (using orthophenanthroline) ranged from 38 to 114 ppm. These results also are shown in Table 17 and are high. They compare with 105 ppm for the very toxic Kilauea soil (used) and with 45 ppm for a moderately toxic soil at Paauhau (FO37), both of which benefited from the application of calcium metasilicate.

Table 17. Bioassay with wheat and other data (soil extract)

Soil number	Degree of chlorosis	Longest root X longest shoot	pH	K ferricyanide test	ppm of Fe in Na_3 EDTA extract
1	very severe	11.7	4.62	+++	74
2	very severe	22.0	4.50	+	44
3	very severe	15.2	4.58	++	61
4	very severe	17.5	4.43	+++	82
5	very severe	10.5	4.32	++++	114
6	very severe	19.6	4.40	+++	74
7	very severe	19.3	4.84	+++	71
8	very severe	8.9	4.35	++++	103
9	severe	12.2	4.56	+++	92
10	very severe	16.2	4.55	++	38
11	severe	12.5	4.25	+++	114
12	very severe	15.8	4.80	++	52
13	none	14.3	4.95	++++	–
14	none	22.0	5.92	0	–
15	virgin soil	9.3	5.60	+	–
16	distilled H_2O	27.3	–	–	–

Total Analysis of Aqueous Extract

The soil extracts were next analyzed for the various elements shown in Table 18, and are reported as ppm of the dry soil but refer only to the water-soluble portion. Ca and Mg are very variable and suggest at least some deficiencies. There is an apparent negative correlation between the wheat-seedling growth and the Fe content of the extract (-.628*) and also with the Al content (-.466[10]). Zn in the orchard soil is from about two to five times higher than in the virgin soil and can also be a part of the toxicity. In separate studies, the 50 percent point in growth depression of wheat seedlings occurred at 10 ppm for Fe^{++} and 15 to 19 ppm for Al, 15 for Cu, 5 for Ni, 30 for Co, and 15 for Zn.

The soil from under tree no. 13, which showed no chlorosis as yet, markedly retarded wheat growth, and this fact together with the abundant Fe^{++}, as reflected by the ferricyanide test and by the markedly higher acidity, probably indicates that chlorosis would develop soon if these conditions were not corrected. The highly chlorotic soil no. 2, which gave good wheat growth, showed a low ferricyanide test and low Fe^{++} analysis, but also showed a very low Ca level. This also applies to no. 10 and 12. Soils no. 1, 5, 8, and 12, which gave the poorest growth with wheat and which produced very severe chlorosis with macadamia, gave the highest Fe^{++} readings (Tables 17 and 18) even though the first three had high Ca readings. Thus, these data indicate that the problem is associated with high Fe^{++} and/or low Ca. However, even though Ca may be adequate if very high levels of Fe^{++} exist, toxicity (mainly to the roots) can be lethal.

Table 18. Water-soluble elements of the dry soil (ppm)

Soil number[a]	Fe	Cu	Mn	Ca	Mg	Al	Si	Zn
1	45.0	.4	10.4	70.0	35.0	8.0	110.8	2.2
2	11.4	.4	2.9	27.0	13.1	3.4	86.2	3.7
3	21.8	.5	3.5	55.4	33.1	9.8	87.2	2.0
4	27.8	.3	10.6	54.2	30.8	5.4	102.0	2.0
5	46.8	.5	8.4	109.4	66.8	12.0	128.0	2.6
6	32.0	.3	9.6	57.4	38.4	3.6	106.8	2.4
7	16.0	.6	2.6	42.4	29.9	13.8	76.8	2.5
8	49.6	.5	10.4	108.4	54.7	10.8	135.6	2.4
9	29.6	.4	4.0	121.2	96.6	22.4	162.2	3.4
10	8.0	.6	2.4	37.4	13.5	4.6	70.2	1.0
11	37.2	.3	6.0	103.8	75.4	22.4	171.2	2.8
12	9.8	.4	1.8	35.8	28.0	9.6	93.4	1.0
13	32.4	.4	9.8	67.2	67.6	9.4	137.4	3.0
14	1.6	0	1.2	45.8	7.9	2.0	132.4	0.7
15	12.0	.2	5.1	149.0	68.4	5.0	87.6	0.6

[a]*See* Table 17 for severity of chlorosis.

It seems rather clear so far that, in the operation ot the orchard over the 15-year period, the practices followed tended to increase rather substantially the soil acidity from 5.6 to around 4.2 to 4.6 and caused the increase in the amounts of Fe and Al in the soil solution while reducing the Ca and Mg levels. Perhaps also because of efforts of management to develop a hard and smooth soil surface to facilitate machine harvest, some tendency toward limiting air penetration into the soil resulted in at least partial anaerobic conditions, permitting greater accumulation of the very toxic ferrous iron. From the analysis of the extract of the virgin soil, it is clear that near-toxic levels (for wheat) already existed at the start.

A review of fertilizer practices from the start of the orchard showed that sulfate of ammonia (SA) was used from 1949 to about 1960. During this period various minor elements and magnesium were applied together with superphosphate (CaP). From 1960, the SA was reduced in quantity but all the calcium phosphates were replaced with Dimon (DAP).

In retrospect it seems clear that the continued use of SA, followed by the shift away from calcium phosphate to DAP, subjected the trees to large amounts of residual acidity. Finally, the elimination of all Ca would hasten the accumulation of toxic elements while reducing the ability of the nutrient-absorption mechanism to prevent the uptake of the toxicants. It is also possible that the continued use of at least some minor elements resulted in some excesses.

Soil Culture Studies

In order to check out the various possibilities developed so far, and after some preliminary attempts, a factorial experiment was designed. Six fertilizer materials were used, each one containing K_2SO_4 (except no. VI) as well as $MgSO_4$: I–SA, DAP; II–urea, DAP; III–SA, CaP; IV–urea, CaP; V–$Ca(NO_3)_2$m CaP; VI–potassium nitrate (KNO_3), urea, CaP.

All the fertilizer mixtures were made of C.P. reagent chemicals and were calculated to give 500 pounds N, 175 pounds P, 290 pounds K, and 10 pounds of Mg per acre.

Three supplements or soil correctives from C.P. chemicals were applied at four levels each: A–calcium carbonate, B–calcium metasilicate, and C–magnesium carbonate. The amounts of each used were calculated to give the neutralizing power of 0, 5, 10, and 15 tons of $CaCO_3$ per acre.

The minor elements, Mn, Cu, B, Mo, and Zn, were also included and were calculated to give 5 pounds of element per acre and Mg at 10 pounds per acre.

The experiment was designed for six fertilizer mixtures, three supplements at four levels and one minor element treatment with two replications, and thus became a 6 X 3 X (4 + 1) X 2 factorial for a total of 180 plots. Each plot was a 1-pint plastic container capable of holding 550 g of oven-dried equivalent Keaau soil. A single 3-mm hole about halfway up on one side provided adequate drainage.

Soluble fertilizers and minor elements were made up in stock solutions and applied by pipette. The supplements and the calcium phosphate were weighed out to 0.01 g and applied as dry material. In all cases, after the fertilizer and supplements were applied, the soil was thoroughly mixed and returned to the containers, watered with distilled water, seal covered, and allowed to incubate at greenhouse temperatures (70 to 100 F) for 2 weeks, after which the containers were uncovered and allowed to dry out to a moderate degree. The soil again was thoroughly mixed, returned to the pot, seeded with five cucumber seeds, and placed in the greenhouse in a completely randomized manner within each block. Watering as needed was done with distilled water. The seedlings were thinned to three per pot.

Twenty-five days later the experiment was harvested by cutting the plants just above the soil line. The green weights were obtained at once. Results are shown in Tables 19, 20, and 21 as averages per pot. In each summary the replications represented per item may be obtained by dividing 180 by the number of items. Thus, within Table 19 there are 18 items, meaning that each one is an average of 10 separate plots. The three averages underneath represent 60 each, and the six averages in the vertical column at the right represent 30, etc.

Variance analysis revealed highly significant differences among fertilizers, and amounts of supplement. Differences among the supplements were not significant. Minor elements reduced growth for fertilizers I to V, but gave the highest actual pot yield with fertilizer VI.

The summary of the fertilizer responses is shown in Table 22. Yields for fertilizer treatments varied from 22.6 for fertilizer III to 44.07 grams for VI. Fertilizers V and VI, made up of the basic cations Ca, K, and Mg, but containing no ammonium and only a small amount of urea in one case, gave the highest yields. It

Table 19. Green weights (grams per pot) for fertilizer X supplements

		Supplements			
		$CaCO_3$	$CaSiO_3$	$MgCO_3$	
Fertilizers		A	B	C	Average
I	SA, DAP	25.1	26.9	24.7	25.5
II	Urea, DAP	36.5	37.8	28.1	34.1
III	SA, CaP	23.6	21.3	22.9	22.6
IV	Urea, CaP	38.4	39.0	42.3	39.9
V	$Ca(NO_3)_2$, CaP	40.6	43.4	47.9	44.0
VI	KNO_3, urea, CaP	49.0	42.6	40.6	44.1
Average		35.5	35.2	34.4	

Table 20. Green weights (grams per pot) for supplement X amounts and minor elements

			Tons of supplement per acre				
Supplement		Minor element	0	5	10	15	Average
A	$CaCO_3$	25.5	32.7	42.0	37.7	39.8	35.5
B	$CaSiO_3$	30.4	30.8	37.0	37.9	39.9	35.2
C	$MgCO_3$	27.1	32.9	34.6	40.1	37.4	34.4
Average		27.7	32.1	37.9	38.6	39.0	

Table 21. Green weight (grams per pot) for fertilizer X amount of supplement and minor element

			Tons of supplement per acre				
Fertilizers		Minor element	0	5	10	15	Average
I	SA, DAP	24.8	14.0	31.3	34.7	23.0	25.6
II	Urea, DAP	29.5	17.7	32.7	41.3	49.5	34.1
III	SA, CaP	13.8	21.5	22.7	28.2	26.8	22.6
IV	Urea, CaP	35.7	34.5	42.8	41.5	45.0	39.9
V	$Ca(NO_3)_2$, CaP	38.5	40.3	49.8	44.8	46.3	44.0
VI	KNO_3, urea, CaP	50.2	38.0	47.8	40.8	43.5	44.1
Average		27.7	32.7	37.9	38.6	39.0	

Table 22. Green weights (grams per pot) for fertilizers X amounts of supplements and minor elements

Treatment	Fertilizer combination (all included equal amounts of $MgSO_4$ and K)		Green weight yield (grams per pot)
III	SA, CaP		22.6 (e)
I	SA, DAP		25.5 (d)
II	Urea, DAP		34.1 (c)
IV	Urea, CaP		39.9 (b)
V	$Ca(NO_3)_2$, CaP		44.0 (a)
VI	KNO_3, urea, CaP		44.1 (a)
		HSD	2.7

Table 23. Green weight (grams per pot) for supplements

Supplement		Green weight yield (grams per pot)
A	Calcium carbonate	35.5
B	Calcium silicate	35.1
C	Magnesium carbonate	34.4
		n.s.

is clear that the yields decline as the amounts of ammonium salts are increased and as the Ca is reduced. Fertilizer III, with calcium phosphate, was less good than fertilizer I, with diammonium phosphate, probably because all of the N in III was from the sulfate.

Variance analysis shows no differences in yield among the three supplements (Table 23).

There was, however, a highly significant response to amounts of the supplements (Table 24).

Thus, the 5-ton treatment of any one of the supplements gave a highly significant response over none, but the minor elements definitely depressed growth, the loss being highly significant ($F = 155.50^{**}$). None of the possible interactions achieved significance.

Effect of Treatments on Soil pH

After the crop was harvested, soil pH determinations were made (Table 25). Fertilizers had a very significant effect on soil pH ($F = 20.73^{**}$). Thus, the pH of the particular composited soil used had an initial pH of 4.95. Fertilizer I, which had

Table. 24. Response to amounts of supplements

Amount of supplement (tons per acre)		Green weight yield (grams per pot)
0 + minor elements		27.7 (c)
0		32.7 (b)
5		37.9 (a)
10		38.6 (a)
15		39.0 (a)
	HSD	2.3

Table 25. Effect of fertilizers on soil pH

Fertilizers			Soil pH
I	SA, DAP		4.58 (c)
III	SA, CaP		4.70 (b) (c)
IV	Urea, CaP		4.78 (b)
II	Urea, DAP		4.87 (b)
VI	KNO_3, urea, CaP		4.87 (b)
V	$Ca(NO_3)_2$, CaP		5.17 (a)
		HSD	.18

the N in the form of ammonium sulfate and diammonium phosphate, was the most acid. Fertilizer III, which had only SA and CaP, was next. Then fertilizers III, IV, and VI, in which calcium phosphate provided the phosphate, and II, containing urea and DAP, were grouped from 4.70 to 4.87. Fertilizer V, with calcium nitrate, calcium phosphate, potassium sulfate, and magnesium sulfate, actually added basicity to the soil, as would be expected, and is superior to VI in which potassium nitrate and urea provided the N.

As with yield, the three supplements which were applied according to a uniform neutralizing power had the same effect on pH. Thus, A—4.88, B—4.82, and C—4.82 are statistically the same.

The amounts of supplements used, however, affected the pH significantly, Table 26 ($F = 20.54^{**}$). It should be remembered that only the "fines" of the soil were used and that this constituted 17.7 percent of the total. The relatively small change in the pH readings points to a very stable buffer system in the soil fraction. The minor element culture showed a pH of 4.79. Undoubtedly, the regression on pH would have been steeper had more time elapsed.

Table 26. Effect of amounts of supplements on soil pH

Amount of supplement (tons per acre)		Soil pH
0		4.64 (c)
5		4.75 (b) (c)
10		4.84 (b)
15		5.12 (a)
	HSD	0.14

There was an interaction between fertilizer and amounts of supplements (F = 4.91**). The data are shown in Table 27. Very clearly, the SA- and DAP-fertilized plots (I, II, and III) responded much more slowly to neutralization than did the others. Fertilizer V, in which $Ca(NO_3)_2$ provided all the nitrogen, had the steepest regression.

To gain some further knowledge of the buffering capacity of the soil, the material which passed the ¼-inch screen (this was 17.7 percent of the original) was screened again through a 4-mm screen. Most of the material (81.6 percent) passed, thus representing about 14 percent of the original field material. Treating 25 grams of soil (1:5) with quantities of $Ca(OH)_2$, ranging in 40-mg increments from zero to 200, gave the data shown in Table 28.

In applying these data to field applications, considerable experimentation is needed, for it must be emphasized that the fines used represent only about 14 percent of the total field mass. If 9.35 tons were applied per acre, a much greater

Table 27. Soil pH interactions for fertilizers X amounts of supplements

	Tons of supplement			
Fertilizer	0	5	10	15
I	4.59[a]	4.25	4.55	4.73
II	4.66	4.89	4.78	5.04
III	4.94	4.65	4.50	4.80
IV	4.42	4.61	4.82	5.23
V	4.59	5.22	5.46	5.74
VI	4.70	4.85	4.93	5.21

[a]Each datum is the average of six separate determinations.

Table 28. Buffering capacity of the Keaau soil fines

$Ca(OH)_2$ (mg/25 g of soil)	Equivalent tons $CaCO_3$ per acre	Soil pH (1–5)
0	0	5.75
40	1.87	6.10
80	3.74	6.42
120	5.61	6.70
160	7.48	6.87
200	9.35	7.20

pH change could result, since so far as the fine fraction is concerned this would be the equivalent of some 65 tons per acre, and this could cause major problems.

General Conclusions and Recommendations

The problem of chlorosis at Keaau is the direct result of two main things: the nature of the virgin substrate to begin with, and the continued use of ammoniacal fertilizer salts without appropriate Ca additions to neutralize the accumulating acidity and to fortify the tree's ability to withstand the severe toxicities of Fe^{++} and Al. Secondary factors include the possibility that the continuing efforts at making the surface smooth by applying volcanic cinders and pressing them in has developed a surface seal restraining free access of air to the rhizosphere, resulting in accumulation of Fe^{++} in the soil solution and reduction of root vigor. Considering the marked setback in growth of the cucumber plants by the addition of minor elements, it is likely that the prolonged use of the several minor elements added to the total toxicity which finally overcame the roots.

The solution to the problem rather clearly requires a shift away from acid-producing fertilizers and toward a Ca regime. This can be accomplished by using either single or treble superphosphates and a judicious but continuing program of calcium carbonate (coral stone). Urea would yield less residual acidity than either the sulfate or phosphate of ammonia. Some effort should be undertaken, experimentally at least, to rough up the surface after each harvest to facilitate air movement into the soil. Also, some effort should be made to mix the carbonate as well as the single or treble superphosphate into at least 2 to 3 inches of the rocky medium, and thus enable the surface roots to establish actual contact with the Ca.

When the Keaau problem is compared with the Kilauea freckling, the similarities in soil solute composition cause one to wonder why each of the three supplements used was equally effective, while at Kilauea, only the silicate was effective. A possible hypothesis which cannot now be pursued might well be associated with the degree of weathering of the two media, resulting perhaps in the surfaces of the Kilauea soil particles being as toxic as the solution itself. Thus, the SiO_2 content of the aa lava being much higher than that of the highly weathered soil suggests that surfaces in the one case are mostly SiO_2, while in the other, Fe^{++}, Fe^{+++}, and Al predominate.

MAUI SUGARCANE GROWTH FAILURE

Maui growth failure (MGF) is a name given a malady of sugarcane growing in central Maui. As the name suggests, complete growth failure of some varieties has been observed. During the early 1920's, McGeorge (*16, 17, 18, 19*) recognized that there was an apparent Ca deficiency and undertook various methods of acidifying the otherwise mildly alkaline soil, but without success.

Martin (*14*), in his book on sugarcane diseases, wrote in part: "The early symptoms [of Maui Growth Failure] are recognized by a slowing up of the growth of the cane and by the presence in the leaves of one or more wide chlorotic stripes that often extend the length of the leaf . . . ." He went on to observe that some varieties withstood the malady better than others, but suggested no causal or remedial factors.

In the 1951 Reports of the Hawaiian Sugar Technologists, Clements (*1*) wrote, "The so-called Maui Growth Failure at Hawaiian Commercial and Sugar Company is another [unexplained] phenomenon . . . . Here, variety H37-1933 is a failure while H44-3098 does pretty well, and H38-2915 is intermediate. Sheath analyses for some varieties growing in the MGF area are:

Variety	*K index*	*Ca index*	*Mg index*
H37-1933	3.40	.138	.498
H38-2915	2.72	.077	.343
H44-3098	3.26	.048	.231

". . .It seems likely that growth failure, of 1933 particularly, is due to magnesium toxicity, and that 3098 does better because it absorbs less magnesium than does 1933. The calcium levels are considerably below normal."

So far the only solution to this problem has been the selection of tolerant varieties which give satisfactory yields although lower than they do in unaffected areas.

Tissue Analysis

In 1968 a search was begun to identify the problem and hopefully find a solution. A half ton of soil was air-dried, screened, and thoroughly mixed by the plantation (Hawaiian Commercial and Sugar Company) and shipped to the University of Hawaii, Department of Plant Physiology. The soil is a Low Humic Latosol made up of a silty loam, often containing gravel and coral sand. The soil has a cation exchange capacity of 21.12 meq/100 g of which 29.3 percent is Ca saturated, 39.4 percent Mg, 8.6 percent K, and 8.2 percent Na for a base saturation of 85.5 percent.

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[2]Essentially this same report was presented to the management of Hawaiian Commercial and Sugar Company on April 29, 1969, in written and oral forms.

Table 29. Crop log data for normal plants and plants distressed by Maui growth failure

			Percent green weight	Percent dry weight		Percent tissue moisture	Percent sugar-free dry weight						Parts per million sugar-free dry weight							Mn/SiO_2 ratio
Field	Variety	Growth	H_2O	TS	LN	K-H_2O	API	Ca	Mg	S	SiO_2	Mn	Zn	Cu	Al	Mo	Fe	B	
901	H50-7209	good	84.5	10.0	1.83	.660	4,134	.080	.115	.235	3.16	23	63	29	11	.89	31	4.2	7
819	H50-7209	bad	82.2	12.2	1.56	.702	13,500	.059	.135	.223	1.99	41	59	14	10	1.14	29	5.8	21
300	H57-5174	good	82.3	9.7	1.49	.530	6,440	.254	.077	.129	2.05	109	30	16	12	.55	9	5.8	53
820	H57-5174	bad	76.2	17.4	1.10	.616	6,834	.088	.094	.159	1.78	19	33	19	13	1.21	27	6.8	11

At the same time, the plantation collected crop log samples of two fairly tolerant varieties (H50-7209 and H57-5174) from MGF areas and also from good land which is capable of maximum yields for the area and sent them to the Brewer Crop Log Laboratory for complete analysis. The results in Table 29 show the dominant problem to be associated with the very low Ca readings. The leaf N readings in the bad areas are obviously very low and no doubt contribute greatly to the poor growth. In the area, in general, aqua ammonia has been the only fertilizer used, since both P and potash levels are very high. The very low readings in the bad areas may well reflect a poor root system as well as a loss of this volatile form of N from the warm and somewhat alkaline soil (pH 7.5 to 7.9). The very low tissue moisture levels reflect not only the poor root system but also the low N. The tissue P readings are very high, as are all the K-H_2O readings. B is rather high. Mg is about normal, although somewhat higher in the poor areas. Zn is quite high, Cu is normal, but Mo is higher in the poor areas. Mn and S tend to be low in both conditions, and Fe is quite low for both the good and bad growth areas, probably a result of the alkaline soil. The total sugars of the sheath are high in the affected areas—a reflection of the low N, low moisture, and poor growth. The low Mn/SiO_2 ratios of 7 and of 11 may well suggest need for Mn in both good and bad areas.

In examining these data, it must be appreciated that the two varieties reported on, especially H50-7209, are fairly tolerant of the malady. The symptoms as seen in the field now are somewhat different than those reported above by Martin in 1938. The younger leaves of an occasional plant are very markedly striped, not unlike that noted for Mn deficiency, and also not unlike that seen on young plants in a serious S deficiency (*5*). The older leaves of some of the 6- to 8-month-old plants have chlorotic stripes throughout the length of the leaf but scattered irregularly across the leaf, leaving some broad and some narrow green bands in between. This symptom also has been obtained in minus-sulfur sand cultures as well as minus-zinc cultures.

Soil Extracts

Distilled water and 1*N* HNO_3 extracts (1:3) were made of the MGF soil. Immediate and copious frothing following the addition of acid indicated the presence of a great deal of carbonate-bicarbonate material. Atomic absorption scanning of the extracts was undertaken, and the concentration of the observed elements determined. The results are shown in Table 30.

Table 30. Elemental composition of 1:3 extracts (ppm)

Extractant	K	Na	Ca	Mg	Fe	Zn	Cr	Ni	Co
H_2O	17	74	3.7	3.8	0.3	0.1	0	0	0.1
1*N* HNO_3	301	217	18.3	7.3	48.7	2.8	1.8	3.3	8.2

It appears quite obvious that the high Na and K would have much to do with the low tissue Ca which, in turn, could increase the Mg level noted earlier for susceptible varieties. Of interest is the high K-H_2O reading, shown in Table 29, for the sheath tissue. The Na index of the same tissue is only 350 ppm, but concurrent studies in sand culture show the Na to accumulate excessively in the roots and stems before rising even a little in the sheaths. Because of the levels of the monovalent cations, the plant finds it difficult to absorb adequate Ca. It is also possible that some elemental deficiencies exist, particularly Mn, and perhaps also S and Zn. Whether this is so because of a lack of the two elements in the soil, or a prevention of their absorption because of the cation disbalance and its effect on the absorption mechanism used by sugarcane, is a part of the problem.

Leaching

Because of the Na in the soil solution, the first obvious thing to do was to leach the soil. A 28-quart plastic basket with four small drainage holes in its bottom was filled with the soil and leached with distilled water for 3 months. The Na content of the particular leachate was 116 ppm at the start, 74 ppm on August 20, 53 ppm on September 9, 41 ppm on September 16, and 14 ppm on October 14.

Preliminary tests with sudangrass showed a marked growth improvement on the leached as contrasted with the unleached soil. Improvement was also obtained when the original soil was treated with 5 tons per acre of gypsum, another common method used in correcting high-sodium soils. It appeared also that a minor element problem did in fact exist and that the particular fertilizer combinations had something to do with determining which minor element in each case was deficient. Therefore, a rather complicated trial was set up, aimed at getting more Ca into the plant and at growth improvement. The general plan of the experiment called for three soil preparations: (I) the untreated soil as received from the plantation, (II) that soil thoroughly mixed with very finely ground gypsum (5 tons per acre), and (III) that soil after leaching with distilled water for 3 months with the Na level in the leachate finally down to 15 ppm.

Seven fertilizer treatments were set up. In each case the application rates were 500 pounds of N, 218 pounds of P, and, except in certain ones, 52 pounds of K per acre:

A. (SA), (DAP), and KCl. This mixture would leave an acid residue and might thus encourage the loss of salts and also provide a stable supply of N and S.

B. $CaCN_2$, (CaP), and KCl. A heavy supply of Ca was thus provided.

C. $Ca(NO_3)_2 \cdot 4H_2O$ ($Ca(NO_3)_2$), CaP, and KCl. Like B, this would provide a large amount of Ca.

D. Urea, CaP, and KCl. Urea was included since it is a common commercial fertilizer used by sugar plantations.

E. Urea, CaP, but no KCl. KCl was omitted because of the high level of K already present. It was included in the other mixtures so that even the leached soil would not be deficient.

F. Urea alone. Since the area by both tissue and soil analysis is classed as a very high-phosphate area as well as a high-potash area, this seemed a reasonable fertilizer. It would have been better to include a NH_4OH treatment, since it is the fertilizer used by the plantation. (This was included in a later test, *see* below.)

G. $CaCN_2$, CaP, and KNO_3. This is a moderately high-calcium fertilizer which gives rise in the soil to urea, and contains no chloride.

Finally, the third factor, the minor elements and Mg were set up as follows: (1) check, (2) $ZnSO_4$, (3) $CuSO_4$, (4) $MnSO_4$, (5) $MgSO_4$, (6) H_3BO_3, and (7) Na_2MoO_4. Applications were made to provide 25 pounds per acre of the element, except for Mo and this was applied at 10 pounds per acre.

Thus, this experiment, a 3 × 7 × 7 with two replications, called for 294 cultures. The pots used were 1-pint square plastic containers which held 780 g of the air-dried soil. After all the chemicals were added, the soil was watered with distilled water and the plastic pots were seal-covered and allowed to incubate. After 2 weeks at greenhouse temperatures, the covers were removed and the soil was allowed to dry out, after which each culture was emptied onto clean paper, the contents thoroughly mixed again, then seeded with sudangrass, and placed in its randomly predetermined position.

Throughout the growth period, watering with distilled water was done as needed. Germination was excellent and all pots were thinned to five plants. In general, growth was good and nothing interfered which precluded getting cogent data reflecting the impact of the several treatments. The sudangrass was harvested on April 14, 1969. Green weights were determined at once and prepared for analysis. A summary of the dry weight yields in relation to treatment follows in Table 31.

Soil treatment gave highly significant yield differences (F = 41.19**) for each treatment with leaching>gypsum>check. Fertilizers also showed highly significant differences (F = 188.63**). The order was as follows: A>C = D>E>G = B>F. For the minor elements (F = 8.44**) the order was Zn>Cu = Check = Mo = Mn = Mg>B. Thus, in the overall, Zn was the only element superior to the check, and B the only element which depressed growth, although, as will be seen later, certain interactions change this. It may, therefore, be stated at this point that Maui growth failure can be overcome by leaching out the Na, using the proper fertilizer combination, and applying at least one minor element, Zn. It is also possible that B, because it depressed growth, may already be present in excessive amounts.

Soil treatments and fertilizers showed a significant (F = 2.54**) interaction, albeit rather weak, Table 32.

Thus, the A fertilizer (SA, DAP, and KCl) was outstanding in all three soil treatments, although slightly better in II than III, the two best treatments in the lot, not significantly different, however. Fertilizer B ($CaCN_2$, CaP, and KCl) did poorly in all three. Fertilizer C ($Ca(NO_3)_2$, CaP, and KCl) was less affected by soil treatment. Fertilizer D (urea, CaP, and KCl) produced rather well in II and III but poorly in I. E (urea and CaP) performed about as well in I and II but better in III. Urea (F) seemed very toxic to growth. This treatment was repeated three different times, and each time the response was the same. Yet, when urea was used together with calcium phosphate and potassium chloride (D), apparently the urea toxicity disappeared even though growth was less good than for A and C. Fertilizer G ($CaCN_2$, CaP, and KNO_3), although not a good combination, showed the average

Table 31. Dry weight yields (grams per pot) by treatments

Soil treatment			Dry weight (grams per pot) (average of 98 yields)
III	Leached		5.10 (c)
II	Gypsum		4.57 (b)
I	Check		3.85 (a)
		HSD	.33

Fertilizer treatments			Dry weight (grams per pot) (average of 42 yields)
A	SA, DAP, KCl		7.24 (e)
C	$Ca(NO_3)_2$, CaP, KCl		5.63 (d)
D	Urea, CaP, KCl		5.59 (d)
E	Urea, CaP		4.94 (c)
G	$CaCN_2$, CaP, KNO_3		3.96 (b)
B	$CaCN_2$, CaP, KCl		3.35 (b)
F	Urea		.84 (a)
		HSD	.62

Minor elements and magnesium treatments			Dry weight (grams per pot) (average of 42 yields)
2	$ZnSO_4$		5.34 (c)
3	$CuSO_4$		4.58 (b)
1	Check		4.53 (b)
7	Na_2MoO_4		4.49 (a) (b)
4	$MnSO_4$		4.35 (a) (b)
5	$MgSO_4$		4.35 (a) (b)
6	H_3BO_3		3.89 (a)
		HSD	.62

trend with soil treatment. It is quite obvious that applying Ca fertilizers will not solve the problem.

Interactions between soil treatments and minor elements were significant. Although soil treatment III was the best for growth, and although Zn gave the highest yield for the minor elements, the highest actual yield in Table 33 is for the

Table 32. Average dry weight yield (grams per pot). Interaction between soil treatments and fertilizers (F = 2.54**) (top yields underscored)

Soil treatment		Fertilizers A	B	C	D	E	F	G	Average
I	Check	6.59	2.68	5.26	4.30	4.30	.62	3.19	3.85
II	Gypsum	<u>7.63</u>	3.35	5.73	6.17	4.56	.34	4.19	4.57
III	Leached	<u>7.49</u>	4.01	5.89	6.30	5.94	1.56	4.49	5.10
Average		7.24	3.25	5.63	5.59	4.93	.84	3.96	

Table 33. Average dry weight yield (grams per pot). Soil treatments × minor element interactions (F = 2.70**) (top yields underscored)

Soil treatment		Check 1	Zn 2	Cu 3	Mn 4	Mg 5	B 6	Mo 7	Average
I	Check	3.88	<u>5.35</u>	3.55	3.63	3.36	3.08	4.10	3.85
II	Gypsum	4.58	<u>5.81</u>	4.76	3.92	4.74	3.89	4.28	4.57
III	Leached	5.15	4.86	<u>5.43</u>	<u>5.50</u>	4.93	4.70	5.11	5.10
Average		4.53	5.34	4.58	4.35	4.35	3.89	4.49	

gypsum-treated soil with Zn, but the untreated soil with Zn also did relatively well, even better than the leached soil with Zn. Leached soil did its best in combination with Cu and Mn, and its loss with Zn will be explained later.

Table 34 shows the fertilizers by minor elements and Mg interactions. The best growth was obtained in the A-2 combination with A-7, A-1, and A-3 following in order. Fertilizers C and D also did relatively well with Zn, but fertilizer A with Zn was the best combination of these two treatments.

Summarizing this experiment, using gypsum at the rate of 5 tons per acre, fertilizer A and Zn appeared to give the best growth but only slightly better than leaching. Leaching the soil resulted in A fertilizer doing best with Cu and Mn. Not treating the soil at all, but using fertilizer A and Zn, did relatively well. Such, then, are the combinations from which plantation management may select one or more practices for field experimentation and correction of MGF.

As a final check, since some of the soil supply remained, several 5-quart plastic pails were filled, and seven different fertilizer combinations were applied to give 500 pounds N and 218 of P per acre. Sudangrass again was used, and final thinning

Table 34. Average dry weight yield (grams per pot). Fertilizers X minor elements and magnesium interactions (top yields underscored)

		Check	Zn	Cu	Mn	Mg	B	Mo	
	Fertilizers	1	2	3	4	5	6	7	Average
A	SA, DAP, KCl	<u>7.55</u>	<u>8.07</u>	<u>7.51</u>	6.95	6.74	6.09	<u>7.76</u>	7.24
B	$CaCN_2$, CaP, KCl	3.06	3.61	3.56	3.41	3.19	2.98	3.62	3.35
C	$Ca(NO_3)_2$, CaP, KCl	5.55	<u>7.42</u>	5.98	5.32	4.95	4.35	5.85	5.63
D	Urea, CaP, KCl	5.40	<u>7.14</u>	5.17	4.76	5.72	5.22	5.74	5.59
E	Urea, CaP	5.16	6.29	5.00	5.21	4.52	4.53	3.85	4.93
F	Urea	.74	.81	.96	.92	1.04	.66	.77	.84
G	$CaCN_2$, CaP, KNO_3	4.28	4.06	3.91	3.88	4.28	3.41	3.89	3.96
Average		4.53	5.34	4.58	4.35	4.35	3.89	4.49	

Table 35. Average green weight yield of sudangrass (grams per pot)

Fertilizers	Soil treatments	Yield of sudangrass (green weight per culture)
$SA, DAP, ZnSO_4$	Leached	330
	Gypsum	275
	Check	318
SA + DAP and all the minor elements except boron	Leached	351
	Gypsum	250
	Check	266
DAP + $ZnSO_4$	Leached	349
	Gypsum	–
	Check	239
SA + DAP	Leached	320
	Gypsum	–
	Check	242
SA + $ZnSO_4$	Leached	224
	Gypsum	36
	Check	75
Urea + $ZnSO_4$	Leached	135
	Gypsum	50
	Check	63
Aqua ammonia + $ZnSO_4$	Leached	129
	Gypsum	–
	Check	48

to 15 plants per culture was effected. In Table 35, the green weight yield of the sudangrass as obtained is recorded along with the fertilizers and supplements used.

Urea was included again, and again, even with $ZnSO_4$, gave very poor growth; in fact, it produced a very toxic condition. However, aqua ammonia with $ZnSO_4$ also produced very poor growth. Using DAP for all the N (and this provided some extra phosphate) and $ZnSO_4$ gave the best growth on leached soil along with SA, DAP, and all the minor elements except B. SA with $ZnSO_4$ was very inferior to DAP with $ZnSO_4$ or DAP with SA, pointing to some very specific role being played either by the phosphate ion or by the ammonia supplied by a phosphate ion, even though the soil and plants were very rich in phosphate. As in the previous set of data, using SA, DAP, and $ZnSO_4$, the untreated soil gave fairly satisfactory yields.

In this study the gypsum treatment did not show up very well. Since the leached soil was superior in all treatments, the yields for it are listed alone in Table 36.

Table 36. Average green weight of sudangrass (grams per pot) on leached soil with various fertilizers

Fertilizers	Yield of sudangrass (green weight per culture)
SA + DAP and all the minor elements except boron	351
DAP + $ZnSO_4$	349
SA + DAP + $ZnSO_4$	330
SA + DAP (no $ZnSO_4$)	320
SA + $ZnSO_4$	224
Urea + $ZnSO_4$	135
Aqua ammonia + $ZnSO_4$	129

Again, DAP with or without SA but with Zn shows the best results and undoubtedly points the way toward maximum yields in the MGF areas, even though there are excessive amounts of P already in the plant and soil.

Effect of Treatments on the Absorption of the Various Nutrients by Sudangrass

In order to seek reasons for some of the interactions, a complete nutrient analysis of the sudangrass was made after the dry weight data were obtained for the first sudangrass series (Tables 31 to 34). The P contents by treatment are shown in Table 37.

Leaching the soil, although giving the best growth, resulted in lowest P. The Zn treatment, also giving the best growth of the minor elements, had the lowest P level. Most of these differences, however, are dilution effects. Of all the fertilizers, SA, DAP, and KCl gave the highest yield and had the highest level of P, and this may well be significant, but fertilizer B which had next to the lowest yield had next to the highest P. There seems little relation between the P content and actual growth

Table 37. Phosphorus content of sudangrass by treatment (percent dry weight)

Soil treatment	Percent P		Fertilizers	Percent P		Minor elements	Percent P
Check	.118 (c)	A	SA, DAP, KCl	.147 (c)	4	Mn	.109 (b)
Gypsum	.111 (b)	B	$CaCN_2$, CaP, KCl	.112 (b)	3	Cu	.106 (b)
Leached	.079 (a)	G	$CaCN_2$, CaP, KNO_3	.108 (b)	5	Mg	.105 (b)
HSD	.005	D	Urea, CaP, KCl	.091 (a)	6	B	.105 (b)
		F	Urea	.088 (a)	7	Mo	.104 (b)
		E	Urea, CaP	.086 (a)	1	Check	.099 (a)
		C	$Ca(NO_3)_2$, CaP, KCl	.086 (a)	2	Zn	.090 (a)
			HSD	.0099		HSD	.0099

Table 38. Calcium content of sudangrass by treatment (percent dry weight)

Soil treatment	Percent Ca		Fertilizers	Percent Ca		Minor element	Percent Ca
Gypsum	.342 (c)	F	Urea	.373 (e)	6	B	.321 (c)
Leached	.295 (b)	C	$Ca(NO_3)_2$, CaP, KCl	.355 (d)	5	Mg	.313 (c)
Check	.268 (a)	E	Urea, CaP	.297 (c)	1	Check	.307 (b) (c)
HSD	.007	D	Urea, CaP, KCl	.283 (b)	3	Cu	.301 (b) (c)
		B	$CaCN_2$, CaP, KCl	.272 (b)	7	Mo	.299 (b)
		A	SA, DAP, KCl	.270 (a) (b)	4	Mn	.297 (b)
		G	$CaCN_2$, CaP, KNO_3	.623 (a)	2	Zn	.275 (b)
			HSD	.013 (a)		HSD	.013 (a)

made, yet the presence of excess P in the medium was a very important part of the solution.

Raising the Ca level (Table 38) by gypsum and leaching did raise the yield, but the A fertilizer had the lowest Ca reading, and Zn, which gave the best yield increase, had the lowest Ca level. It would seem that leaching away the excess soluble salts corrected the Ca absorption problem adequately. Urea, which gave stunted growth, had the highest Ca.

With a pH near 8.0 (Table 39), Fe might well be in deficient supply, but with leaching raising the acidity and with fertilizer A contributing to more acidity (*see below*), problems should not develop. Urea alone, which was toxic and gave very poor growth, greatly increased the concentration of Fe in the plant. The addition of calcium phosphate to urea with or without K resulted in the lowest Fe level and much improved growth.

Table 39. Iron content of sudangrass by treatment (ppm dry matter)

Soil treat-ment	ppm Fe		Fertilizers	ppm Fe	Minor element	ppm Fe
Check	270 (b)	F	Urea	495 (c)	6 B	266 (b)
Gypsum	261 (b)	B	$CaCN_2$, CaP, KCl	251 (b)	5 Mg	260 (b)
Leached	171 (a)	G	$CaCN_2$, CaP, KNO_3	199 (a) (b)	1 Check	240 (a) (b)
HSD	30	A	SA, DAP, KCl	192 (a)	3 Cu	237 (a) (b)
		C	$Ca(NO_3)_2$, CaP, KCl	180 (a)	7 Mo	221 (a) (b)
		E	Urea, CaP	166 (a)	2 Zn	210 (a) (b)
		D	Urea, CaP, KCl	156 (a)	4 Mn	204 (a)
			HSD	56	HSD	56

Table 40. Sulfur content of sudangrass by treatment (percent dry matter)

Soil treat-ment	Percent S		Fertilizers	Percent S	Minor element	Percent S
Gypsum	.122 (b)	B	$CaCN_2$, CaP, KCl	.085 (b)	5 Mg	.088 (b)
Leached	.056 (a)	G	$CaCN_2$, CaP, KNO_3	.085 (b)	6 B	.079 (a) (b)
Check	.054 (a)	A	SA, DAP, KCl	.083 (b)	3 Cu	.078 (a) (b)
HSD	.005	C	$Ca(NO_3)_2$, CaP, KCl	.075 (a) (b)	4 Mn	.076 (a)
		D	Urea, CaP, KCl	.073 (a)	2 Zn	.073 (a)
		F	Urea	.072 (a)	1 Check	.073 (a)
		E	Urea, CaP	.068 (a)	7 Mo	.072 (a)
			HSD	.010	HSD	.010

Leaching had no effect on S (Table 40), but gypsum did, and if S deficiency does occur as a part of the growth failure complex, then leaching by itself would fail to correct the problem entirely. The use of SA raised the S significantly, even though rather little. Mg, B, and Cu each raised the S levels.

The only outstanding effect on B (Table 41) was that of the addition of B which more than tripled the levels in the plants, which probably accounts for the significant loss of yield (Table 31). Leaching lowered the B levels significantly but relatively little.

Reducing the level of K (Table 42) is desirable because of the high amounts of the element in the soil. Leaching, of course, lowered it the most, but gypsum also lowered it, though not so effectively. Fertilizers E, D, A, and C also lowered it. Minor elements had no effect.

Table 41. Boron content of sudangrass by treatment (ppm dry matter)

Soil treatment	ppm B		Fertilizers	ppm B		Minor elements	ppm B
Check	27.17	F	Urea	29.2 (b) (c)	6	B	74.1 (b)
Gypsum	26.16 (a) (b)	A	SA, DAP, KCl	27.6 (b) (c)	7	Mo	19.1 (a)
Leached	24.31 (a)	B	$CaCN_2$, CaP, KCl	26.7 (a) (b) (c)	3	Cu	18.5 (a)
HSD	2.21	G	$CaCN_2$, CaP, KNO_3	25.3 (a) (b) (c)	5	Mg	17.7 (a)
		E	Urea, CaP	24.9 (a) (b)	4	Mn	17.7 (a)
		D	Urea, CaP, KCl	24.5 (a) (b)	1	Check	17.0 (a)
		C	$Ca(NO_3)_2$, CaP, KCl	22.9 (a)	2	Zn	17.0 (a)
			HSD	4.2 (a)		HSD	4.2

Table 42. Potassium content of sudangrass by treatment (percent dry matter)

Soil treatment	Percent K		Fertilizers	Percent K		Minor elements	Percent K
Check	2.84 (c)	F	Urea	3.30 (c)	6	B	2.64
Gypsum	2.68 (b)	G	$CaCN_2$, CaP, KNO_3	2.68 (b)	7	Mo	2.63
Leached	2.26 (a)	B	$CaCN_2$, CaP, KCl	2.65 (b)	3	Cu	2.61
HSD	.08	E	Urea, CaP	2.44 (a)	4	Mn	2.60
		D	Urea, CaP, KCl	2.39 (a)	1	Check	2.60
		A	SA, DAP, KCl	2.38 (a)	5	Mg	2.58
		C	$Ca(NO_3)_2$, CaP, KCl	2.33 (a)	2	Zn	2.50
			HSD	.16			n.s.

Since a Zn application improved growth in the check and gypsum treatments but not in the leached soil (Table 43), it is interesting that, somehow, leaching enabled the plant to absorb much more Zn. It might be suggested that, just as Na, perhaps together with K, prevented the ready absorption of Ca, so they also depressed the absorption of Zn. Because gypsum failed to increase Zn uptake very much, and because the A fertilizer also failed to affect Zn uptake, the application of Zn to these treatments resulted in a marked stimulation of growth.

Soil pH Changes

To determine the effect on soil pH which various commercial fertilizers could have, quantities of soil from Hawaiian Commercial and Sugar Company were placed into 5-quart plastic pails without a provision for drainage. Amounts of fertilizer

Table 43. Zinc content of sudangrass by treatment (ppm dry matter)

Soil treatment	ppm Zn		Fertilizers	ppm Zn		Minor elements	ppm Zn
Leached	44.68 (c)	F	Urea	57.0 (c)	2	Zn	40.1 (b)
Gypsum	28.98 (b)	E	Urea, CaP	32.8 (b)	6	B	33.8 (a)
Check	27.52 (a)	D	Urea, CaP, KCl	31.7 (b)	7	Mo	33.1 (a)
HSD	1.25	C	$Ca(NO_3)_2$, CaP, KCl	30.5 (a) (b)	3	Cu	32.9 (a)
		B	$CaCN_2$, CaP, KCl	28.8 (a) (b)	1	Check	32.8 (a)
		G	$CaCN_2$, CaP, KNO_3	28.0 (a)	5	Mg	32.0 (a)
		A	SA, DAP, KCl	27.5 (a)	4	Mn	31.6 (a)
			HSD	3.7		HSD	3.7

added provided N and P in very large amounts, equivalent to about 12 crops. Soil pH readings were taken at various intervals of time, but are reported for only three (Table 44). After about 8 months and with the untreated soil showing a pH of 7.42, the most acid fertilizer was ammonium nitrate and DAP, followed in order by SA, DAP, and KCl; SA and treble superphosphate; 16-16-16; tripolyphos; ammonium nitrate and ammophos; ammonium chloride and DAP; DAP alone; and ammonium

Table 44. Effect of various fertilizers on pH of MGF soil (original pH–7.50)

Fertilizers	pH at: 8/30/68	12/24/68	4/17/69
Check	7.50	7.35	7.42
$CaCN_2$	8.00	7.80	7.12
Nonammonium fertilizer	6.78	6.30	6.85
KNO_3 and treble superphosphate and $Ca(NO_3)_2$	6.40	6.20	6.15
Ammonium chloride and treble superphosphate	5.60	5.65	5.12
Diammonium phosphate	6.80	5.31	4.42
SA and ammophos	5.59	4.53	4.40
Ammonium chloride and DAP	6.10	5.20	4.35
Ammonium nitrate and treble superphosphate	5.27	4.95	4.30
Tripolyphos	5.45	4.87	4.25
16-16-16	5.55	4.10	4.19
SA and treble superphosphate	5.24	4.92	4.14
SA, DAP, and KCl	6.14	4.70	4.08
Ammonium nitrate and DAP	5.80	4.73	3.72

chloride and treble superphosphate. Calcium nitrate, potassium nitrate, and treble superphosphate; a nonammonium mixture (made up of Ca and K nitrates with K phosphates and KCl); and calcium cyanamid had some acidifying qualities, although they would normally be expected to add basicity.

Undoubtedly, one reason fertilizer A (SA, DAP, and KCl) essentially overcame Maui growth failure was not only the addition of the elements themselves but also the change in pH which would have a marked effect on nutrient absorption.

General Conclusions and Recommendations

It seems rather clear that Maui growth failure is the result of several interacting factors, and that several avenues are available for its correction. High levels of Na as well as K have tended to reduce the Ca as well as the Zn and sulfate levels of the plants. Leaching was superior to gypsum in correcting the monovalent cation problem, but gypsum increased both the Ca and sulfate uptake perhaps more than necessary. The use of ammonium sulfate and diammonium phosphate, or the latter alone, not only tended to acidify the soil but also played some unknown role in the absorption process, which improved the Ca uptake. Because leaching somehow greatly increased the level of Zn in the plants, this element was important only on the untreated and gypsum-treated soil. Leaching, however, resulted in need for additions of Mn and perhaps also Cu. B was definitely harmful, perhaps indicating something of an excess in the natural soil.

Choices by management for the correction of MGF are several. Leaching would undoubtedly have the most permanent effect, particularly if the pump water normally used could be improved in quality. It would not matter whether this is done during winter months when mountain water supplies are excessive or during regular crop production by using fresh mountain water for irrigation. Even irrigating during the winter months with mountain water would be helpful. Actually, the fields involved are irrigated entirely with water pumped from within the MGF area itself, resulting in a recycling of the affected water. Perhaps, also, some studies might be undertaken to use excess mountain water in the winter to dilute the ground water supplies by direct flow downward into the ground water basin, thus using the underground as a massive fresh water reservoir for mountain water.

Gypsum may also find a place, particularly in localized areas shown to be low in tissue Ca and S. The use of diammonium phosphate, perhaps a superior N source, seems so outstanding in the experiments reported that, even though phosphate levels in cane already seem high, an intensive program of field demonstration and study should be undertaken. Even using no soil treatment at all, but using diammonium phosphate for all the N and adding Zn, would seem certain to be helpful. If leaching is done, perhaps Zn would not be needed, but then attention should be focused on the needs for Mn and Cu.

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