PLANT NUTRIENTS FROM SLAG

Furnace Slag as a Source of Plant Nutrients and Its Liming Effectiveness Relative to Limestone

P. P. CHICHILO, W. H. ARMIGER, A. W. SPECHT, and C. W. WHITTAKER

Bureau of Plant Industry, Soils, and Agricultural Engineering, Agricultural Research Administration, U. S. Department of Agriculture, Beltsville, Md.

A study was made of absorption by crops of some elements contained in blast furnace slag used for soil liming or supplied by the soil or the added fertilizer. The chemical composition of sweetclover crops produced on soils limed with slag was compared with that of such crops produced on soils limed with a pure limestone that supplied only insignificant quantities of the elements (except calcium) supplied by the slag. On a heavy loam soil slag liming produced crops containing, percentagewise, 2 to 4 times as much manganese, less calcium, and frequently more copper. On this soil and on a sandy loam it produced crops containing up to 2.5 times as much magnesium and significantly more boron. Aluminum, iron, and sodium contents were unaffected within the accuracy of the tests, and phosphorus and potassium contents in only a few comparisons. As judged by yield and soil pH, the slag was as effective a liming material on the sandy loam as the limestone, but limestone was more effective on the heavy loam. The relative effectiveness of this slag and limestone for liming the soil, as well as their effects on crop composition, may be strongly modified by the kind of soil.

THAT BLAST FURNACE SLAG affects the soil and the yield of crops much as do agricultural limestone and other liming materials has long been recognized. Its liming value was pointed out by Ames (*1*) in 1916, and re-emphasized by others, notably by White, Holben, and Jeffries (*13*) in 1937. The literature, now extensive, was reviewed in 1932 by La Rotonda (*7*), in 1950 by Kappen (*6*), and more recently by Volk, Harding, and Evans (*12*). Most of the published work compares the effects of slag on yield of crops and on soil properties with those of agricultural limestone or other conventional liming materials. MacIntire and associates (*8*) compared it also with phosphorus furnace slag.

The absorption by crops of the trace and other elements found in blast furnace slag has received much less attention. Kappen (*6*, pp. 145–7), however, reviewed work on the silicon and manganese uptake of oats limed with slag. Such absorption is important, not only in relation to the nutritive value of the crop, but because it indicates the availability to crops of elements in the slag. Like other liming materials, slag can be expected to affect indirectly the absorption of other elements derived only from the soil or added fertilizer. All such effects should be most intense in the crop that is grown immediately after liming, usually a legume.

The chemical composition of sweetclover grown on soils limed with blast furnace slag was therefore compared with that of sweetclover grown on the same soils limed with a pure high-calcium limestone. Either material supplied the liming action necessary for crop growth on the acid soils used, and created essentially the same general soil conditions. The slag, however, contained several elements absent from the limestone or present there in only insignificant amounts. Higher concentrations of such elements in the crop when the slag was used are thus presumptive evidence of their having been supplied in available form by the slag. For these elements the limestone-treated soils served as a basis of reference. The question of the availability of such elements when present in a limestone was not considered in this work. For elements not supplied by either liming material, the study afforded a comparison of the effects of slag and limestone on crop absorption of such elements from soil or added fertilizer. For practical reasons the study was limited to elements accurately determinable by spectrographic methods or by the flame photometer.

To make the study as complete as possible, the material for analysis was produced on two soils under varying liming rates and finenesses of the liming materials, and data were recorded on yield, soil pH, and emergence of the plants. As the limestone is a type commonly used for soil liming, another comparison is thus afforded of the liming actions and effects on crop growth of blast furnace slag and of limestone.

Materials and Procedure

The sweetclover was grown in the greenhouse in a $2 \times 2 \times 2 \times 3$ factorial design (two soils, two liming materials, in each of two finenesses, and used at three rates) laid out in three approximately square randomized blocks, located end to end along a greenhouse bench. All crop and chemical data were interpreted as indicated by about 120 analyses of variance.

Soils Two soils of widely different properties were used: a Norfolk sandy loam from an unlimed area of the McCullers Experiment Farm of the North Carolina State College of Agriculture, and a Fallsington heavy loam, poorly drained and believed to be virgin, from a wooded area near Grasonville, Md. The 0- to 8-inch layer of each soil was taken after removing surface trash.

Prior to liming and fertilization, the pH values of the Norfolk and Fallsington soils were, respectively, 5.3 and 4.2; exchangeable hydrogen determined by the barium chloride–triethanolamine method (*9*) was 3.8 and 9.3 meq. per 100 grams; the lime requirements to pH 7, determined by the Schollenberger and Dreibelbis method (*10*), were 2085 and 6585 pounds of calcium carbonate per acre; and potash soluble in normal ammonium acetate of pH 7 amounted to 1617 and 373 pounds per acre.

Slag and Limestone The slag was the air-cooled type from a typical blast furnace operation. Blast furnace slag should not be confused with phosphorus furnace slag, also used for liming, or with basic (Thomas) slag, used mainly as a phosphorus fertilizer. "Slag," as used in this paper, refers specifically to blast furnace slag. The limestone was the high-calcium type, much used for soil liming. Analyses of the two materials are given in Table I. Boron, cobalt, copper, molybdenum, and manganese were determined in these materials as described by Chichilo and Whittaker (*4*). Titanium (not reported) and iron were determined colorimetrically and the values used to correct the weight of R_2O_3 oxides obtained in the aluminum determination. Sulfur was weighed as barium sulfate after oxidation of sulfide sulfur to sulfate by means of bromine. Calcium and magnesium were determined as prescribed by the Association of Official Agricultural Chemists for agricultural liming materials (*2*, p. 3), as were also the calcium carbonate equivalents, using the methods for slag and limestone (*2*, pp. 3 and 1, respectively). Phosphorus, sodium, and potassium, not determined, are present in both the slag and limestone in very small amounts.

The two fineness grades of each material are referred to as "coarse" and "fine." The coarse grade of slag was the material as received, having the sieve analysis shown in Table II, similar to that of rather coarse agricultural limestone. Sieve fractions of the limestone, made by using the sieve pairs listed in the table, were recombined in proportions that gave a coarse limestone with a particle size distribution similar to that of the coarse slag. This was done to avoid any effects due solely to differing fineness of the materials. The fine grade of each material was prepared by simply grinding to pass a U. S. No. 80 sieve. Disparities in sizes of particles that all passed this sieve could hardly be of much importance.

Greenhouse Procedure Enough of each soil to form a 6-inch layer in all the 3-gallon pots used for that soil was mixed in large batches with the required amounts of superphosphate (48% available phosphorus pentoxide) and potassium chloride (50% potassium oxide). The amounts were equivalent to 500 pounds of phosphorus pentoxide on both soils and to 200 and 100 pounds of potassium oxide on the Fallsington and Norfolk soils, respectively. All amounts of fertilizer and of lime were based on the acre-fraction of soil exposed in the pot. Fertilized soil for each individual pot was hand mixed with the amount (calculated from the determined calcium carbonate equivalents) of slag or limestone required to furnish neutralizing power at the rates of 0.5, 1.0, or 1.5 times the lime requirement of the soil. The prepared soil was finally placed in the pot on top of enough untreated soil to bring the final soil level near the top of the pot. The potted soil was maintained at approximately its moisture equivalent for 80 days prior to planting 30 seeds of Yellow Madrid sweetclover in each pot. The stand was thinned to seven plants per pot 38 days after seeding.

The plants were cut 2.5 inches above the soil at 86, 190, 240, 293, and 355 days after planting. A few blooms had appeared on each cutting date. Data from the fourth cutting of the third block were discarded because of accidental loss of plants in some pots, thus reducing the replications from three to two. By the fifth cutting further losses made it necessary to ignore the blocks and make a random selection of two complete replications from the pots remaining. The plant material was oven-dried in paper bags for 24 hours at 65° C., weighed, and ground for analysis.

Table I. Per Cent Composition of Liming Materials

Element	*Form Reported*	*Limestone*	*Blast Furnace Slag*
Aluminum	Al_2O_3	0.30	10.6
Calcium	CaO	55.6	33.6
Magnesium	MgO	0.09	14.8
Manganese	Mn	0.003	1.25
Iron	Fe_2O_3	0.10	1.20
Boron	B	0.0005	0.0090
Cobalt	Co	Trace[a]	Trace[a]
Copper	Cu	0.0002	0.0009
Molybdenum	Mo	Trace[b]	Trace[b]
Sulfur	S	.....	1.16
Calcium carbonate equivalent	$CaCO_3$	99.4[c]	87.2[c]

[a] Probably much less than 1 p.p.m.
[b] Probably less than 0.3 p.p.m.
[c] As actually determined by official methods.

Determination Of Soil pH The pH of the soil in each pot was determined 110, 277, 377, and 476 days after the soils had been limed and moistened. A $^3/_4$-inch cork borer was inserted about 4 inches into the soil while the borer was rotated to avoid pushing the soil ahead of it. The resulting sample was air-dried overnight. Fifteen grams were mixed with 15 ml. of water, and allowed to stand 1 hour, and the pH was read with a Beckman Model G pH meter using glass electrodes. Successive samples were drawn from different pot areas.

Table II. Sieve Analysis of Slag

Sieve Nos. of U. S. Series (Passing-Retained)	*Passing Coarser but Retained on Finer Sieve, %*
8– 10	41[a]
10– 20	19
20– 40	16
40– 60	6
60– 80	4
80–100	2
Passing 100	12

[a] Including a very few particles retained on No. 8 sieve.

Spectrochemical Methods Aluminum, boron, calcium, copper, iron, magnesium, manganese, phosphorus, and sodium were determined simultaneously in the plant material by means of a large Littrow spectrograph equipped with a quartz prism. The previously ground plant material was dried overnight at 95° C., samples weighing 10 or 15 mg. were ashed and then arced in specially prepared electrodes, and the spectra were photographed on the same plates with those of standards of accurately known composition covering the ranges of concentration of elements found in the samples under test. Densities of the spectral lines were determined with a densitometer. Determinations were in quadruplicate on the material from each pot in the first cutting and in duplicate on the second, third, and fifth. Each replicate was placed on a different spectrographic plate. Crop material from the fourth cutting appeared to be contaminated with mineral matter carried in smoke from a nearby heating plant and was not analyzed.

Single flame-photometer determinations of potassium were made on the material from each pot with a Beckman photoelectric spectrophotometer with a Perkin-Elmer flame-atomizer attachment as adapted and modified by Holmes (*5*).

Adequate quantitative spectrographic methods for silica and sulfur were not immediately available and these two elements were therefore not included in the study.

Table III. Soil pH

Liming Material			pH of Soil Indicated Number of Days after Liming							
			Norfolk Soil				Fallsington Soil			
Kind	Fineness	Rate[a]	110	278	377	476	110	278	377	476
Limestone	Coarse	0.5	4.7	5.6	5.7	5.8	4.9	5.4	5.3	5.2
Limestone	Coarse	1.0	5.1	5.9	5.8	5.7	5.2	6.4	6.2	6.3
Limestone	Coarse	1.5	5.0	6.1	6.0	5.8	6.0	7.0	6.7	6.8
Limestone	Fine	0.5	5.3	6.2	5.9	5.6	5.1	6.0	5.6	5.5
Limestone	Fine	1.0	5.7	6.5	6.2	5.9	6.9	7.4	6.9	6.9
Limestone	Fine	1.5	6.0	7.0	6.5	6.3	7.2	7.8	7.6	7.5
Averages for limestone			5.30	6.22	6.02	5.85	5.88	6.67	6.38	6.37
Slag	Coarse	0.5	4.8	5.8	5.8	5.8	4.2	4.5	4.7	4.7
Slag	Coarse	1.0	5.0	6.0	5.9	5.9	4.7	5.0	5.2	5.0
Slag	Coarse	1.5	5.1	6.1	6.1	5.8	5.1	5.8	5.7	5.6
Slag	Fine	0.5	5.1	6.1	5.9	5.9	5.3	5.7	5.6	5.3
Slag	Fine	1.0	5.4	6.3	6.1	6.4	5.8	6.5	6.3	6.1
Slag	Fine	1.5	5.8	6.6	6.4	6.5	6.2	7.0	6.8	6.9
Averages for slag			5.20	6.15	6.03	6.05	5.22	5.75	5.72	5.60
L.S.D.[b] 5% level			0.20	0.16	0.13	0.46	0.25	0.36	0.47	0.49
L.S.D.[b] 1% level			0.27	0.21	0.18	0.63	0.34	0.50	0.64	0.51
Initial pH				5.3				4.2		

[a] In multiples of lime requirement as determined chemically.
[b] Between treatment means.

Emergence, Soil pH, and Yield

The average emergence 9 days after seeding was 50 and 63%, respectively, on the unlimed and limed Norfolk soil and 30 and 43% on the Fallsington soil. It made no significant difference which liming material was used, how fine it was, or how much was applied. All liming treatments improved percentage emergence.

Slag and limestone raised the pH of the Norfolk soil to about the same extent (Table III), but the latter was the more effective on the Fallsington soil. Increasing the liming rate and fineness of each material favored higher pH on both soils. The effect of particle size, however, was sometimes significantly conditioned by the soil and the rate of liming. The maximum pH resulting from most of the treatments had been reached in 278 days and thereafter remained steady or declined slightly.

As an over-all effect, but with exceptions among individual treatment comparisons, limestone produced higher yields than slag in all cuttings from the Fallsington soil (Table IV). On the Norfolk soil the two materials were about equally effective, except that the limestone produced higher yields in the third cutting. The finer grade of each material usually produced higher yields on the Fallsington soil but yield differences were seldom significant on the Norfolk soil. Similarly, rate of liming influenced yield more on the Fallsington than on the Norfolk soil.

Composition of Crops

The average contents of boron, calcium, magnesium, phosphorus, manganese, and copper, found in each cutting from all pots of each soil-liming material combination, are listed in Table V. Each value in Table V is the average of the average contents of an element found in each of 18 pots in the first three cuttings, or of 12 pots in the fifth cutting. The pot averages in turn represent two to four replications. This condensed presentation of the very large mass of data brings out the effects of substituting slag for limestone but, because the data from the three rates of liming and two fineness grades are averaged together, does not afford any test of the effects of these two factors. The analyses of variance of the original data indicated, however, that in most cases the fineness and rate factors were of less importance than the choice of liming material. These factors are discussed only where they assumed definite importance.

Plants on fertilized but unlimed check pots of either soil died soon after emergence, or were very small. Aside from these evidences of soil acidity and/or lack of calcium, there were no apparent symptoms of deficiency of any plant nutrient or nutrients. The very pure limestone used supplied only calcium in significant amounts, yet produced yields equaling or exceeding those produced by the slag.

Boron Boron concentrations in all crops where slag liming was used, except the fifth cutting from the Norfolk soil, averaged 1.3 to nearly 3 times those from the limestone treatments. Greatest differences were shown on the Fallsington soil. The size of the differences was sometimes affected by the rate of liming and the fineness of the liming material. Such effects, however, were not consistently significant and are not discussed here. The results on boron are in line with those of Carter, Collier, and Davis (*3*), who recently reported that slag without added borax produced better yields on boron-deficient soils than limestone without borax.

Calcium and Magnesium Magnesium was regularly present in higher concentrations in all crops from both soils where slag was used than where limestone was used. Calcium, on the other hand, tended to be higher in crops from the limestone-treated soils. This was most pronounced on the Fallsington soil, where the use of limestone produced crops averaging about 1.5 times the calcium concentration of those from slag treatments. On the Norfolk soil the effect could be seen in all cuttings but was significant only in the second. As only the slag contained magnesium, its effect on the magnesium concentration was not surprising. The effect with calcium, however, was unexpected, since both liming materials supplied large amounts of that element.

Phosphorus Phosphorus was supplied by neither liming material in significant amounts but was, nevertheless, of significantly higher concentration in two cuttings from the slag-limed Fallsington soil than from the same soil when limestone was used. The phosphorus contents of the crops on the Norfolk soil were 1.5 to 2 times those on the Fallsington soil, but showed no differences ascribable to the kind of liming material.

Various and somewhat conflicting opinions have been expressed in the literature concerning the effects of active silica, such as that released in the soil by slag, on phosphorus uptake (*7*). The results described here indicate that the phosphorus content of the crop may be enhanced by the presence of such silica under certain conditions.

Manganese Manganese concentrations in crops from the slag-treated Fallsington soil were 2 to 5 times those in crops from that soil when limed with limestone. The work of Tisdale and Bertramson (*11*) suggests, however, that such an effect could have been due solely to the generally lower pH of the slag-treated soil, that would tend to favor uptake of soil manganese, rather than to the manganese content of the slag. This point was checked by a regression analysis of the treatment averages of the manganese and soil pH data, the latter interpolated to cutting dates. Because of an apparent curvilinear relation of these two variables, the logarithms of the manganese values were used. The analysis did, indeed, show a highly significant negative regression of crop manganese on pH with both slag and limestone. This regression was much sharper, however, on the slag-treated soil, indicating that more manganese was taken up in the presence of the slag than of limestone under the same favorable (low) soil pH. After adjustment for pH effect by covariance, the manganese content of the crops from the slag-treated Fallsington soil was still significantly greater than in those from the limestone-treated soil. It thus seems certain that the higher manganese content of crops from the slag-treated soil was due mainly to the slag manganese.

The main effect on manganese concentration of the kind of liming material on the Fallsington soil was conditioned in a complicated manner by the rate of liming and the fineness of the liming material. These two factors and their interactions were frequently highly significant in the analyses of variance. This was probably due to the action of the pH factor. The kind of liming material had no effect on the manganese contents of crops from the Norfolk soil.

Copper The average copper concentrations in crops from slag-limed Fallsington soil were significantly higher in the first two cuttings than when limestone was used. As the slag contained 4.5 times as much copper as the limestone, it is surprising that more and larger differences did not appear. The results were less precise on the third and fifth cuttings, which may have obscured such effects in those cuttings. Copper contents of crops on the Norfolk soil were unaffected by any of the variables in the experiment.

Aluminum And Iron The iron and aluminum concentrations in the plant material were, in general, unaffected by the kind of liming material. This is somewhat surprising in view of the several hundred pounds per acre of active aluminum released in the soil by the decomposition of the slag. The average aluminum contents in the cuttings ranged from 150 to 530, and from 220 to 400 p.p.m., respectively, on the Norfolk and Fallsington soils. The corresponding ranges of iron contents were 190 to 290, and 220 to 270 p.p.m., respectively.

Sodium and Potassium Contents of sodium and potassium in the plant material were, in general, not significantly affected by the factors of the experiment. The average concentration of potassium in the cuttings ranged from 19,300 to 35,900, and from 16,200 to 32,100 p.p.m., respectively, on the Norfolk and Fallsington soils. Corresponding sodium ranges were 43 to 65 and 45 to 87 p.p.m., respectively.

Sources of Error

The total error variance in the crop composition data is that arising from uncontrolled growth factors that may have affected composition, such as differences in plant vigor, soil variation, etc., plus the variance representing the differences among replications in the chemical determinations. The latter comes from variations in composition of the small samples used in the spectrograph, in densitometer readings, uneven reactions in the arc, and so on. As interpretation of the results was based on the total error variance, poor agreement among chemical replicates could thus have concealed real differences in composition that would otherwise have been significant. The relative importance of the analytical precision varies from element to element, so that the judgments were not equally critical in all cases.

For aluminum, boron, manganese, iron, and sodium, the ratios of the total error variance to the determination variance (Table VI) were generally large and highly significant, indicating that real differences in the composition with respect to these elements were probably not concealed by lack of analytical precision. Boron and manganese did show some differences (Table V). True differences for phosphorus, copper, and calcium, however, may have been obscured by relatively low analytical precision. Significant composition differences (Table V) were, of course, shown in many cases in spite of a lack of significance of the corresponding ratio in Table VI. Magnesium, especially, showed this effect.

Systematic errors that would cause consistently high or low results should have had no effect on the observed differences. Such errors were eliminated so far as possible.

Summary and Conclusions

Crop absorption of plant nutrients and other elements from blast furnace slag used to lime the soil was studied by comparing the chemical composition of sweetclover crops produced on two soils limed with slag, with those produced using a limestone that supplied only insignificant amounts of elements con-

Table IV. Yield

(Dry weight of harvested material in grams per pot)

Liming Material			Cuttings				
Kind	*Fineness*	*Rate*[a]	*1st*[b]	*2nd*[b]	*3rd*[b]	*4th*[c]	*5th*[c]
A. Norfolk Soil							
Limestone	Coarse	0.5	13.27	4.38	13.06	12.75	14.53
Limestone	Coarse	1.0	11.44	9.61	24.82	16.02	12.67
Limestone	Coarse	1.5	12.70	13.15	22.11	17.06	14.10
Limestone	Fine	0.5	10.93	9.75	17.48	15.63	13.64
Limestone	Fine	1.0	11.93	19.49	26.74	14.12	12.21
Limestone	Fine	1.5	12.13	15.99	24.20	14.94	19.67
Averages for limestone			12.067	12.062	21.402	15.087	14.470
Slag	Coarse	0.5	12.85	6.22	11.79	13.18	16.31
Slag	Coarse	1.0	10.71	9.24	14.23	14.95	13.02
Slag	Coarse	1.5	8.86	7.52	16.92	13.48	12.60
Slag	Fine	0.5	10.83	9.17	12.33	14.10	9.89
Slag	Fine	1.0	11.66	11.47	14.05	15.66	17.20
Slag	Fine	1.5	13.03	17.61	22.05	16.48	16.66
Averages for slag			11.323	10.205	15.228	14.642	14.280
No lime			8.66	2.73	5.67	7.13	9.89
L.S.D.[d] 5% level			3.84	7.46	9.20	5.78	11.07
L.S.D.[d] 1% level			5.22	10.14	12.50	8.16	15.62
B. Fallsington Soil							
Limestone	Coarse	0.5	5.21	6.65	10.14	12.60	15.73
Limestone	Coarse	1.0	6.76	7.16	16.57	18.50	19.71
Limestone	Coarse	1.5	9.05	9.05	19.66	19.34	22.43
Limestone	Fine	0.5	8.92	8.42	9.27	12.39	16.11
Limestone	Fine	1.0	8.15	14.20	23.24	17.82	22.84
Limestone	Fine	1.5	7.11	10.04	27.23	16.66	21.57
Averages for limestone			7.533	9.253	17.685	16.218	19.732
Slag	Coarse	0.5	2.72	0.96	0.74	0.96	1.42
Slag	Coarse	1.0	4.67	5.27	6.95	10.36	9.13
Slag	Coarse	1.5	6.78	6.79	11.19	15.08	14.53
Slag	Fine	0.5	6.82	10.08	14.64	15.84	16.01
Slag	Fine	1.0	6.00	5.77	11.95	17.52	17.79
Slag	Fine	1.5	8.24	8.93	22.91	20.58	22.98
Averages for slag			5.872	6.300	11.397	13.390	13.643
No lime			1.11	0.88	0.75	1.49[e]	0.85
L.S.D.[d] 5% level			3.11	7.02	9.75	5.92	6.97
L.S.D.[d] 1% level			4.23	9.55	13.25	8.36	9.83

[a] In multiples of lime requirement as determined chemically.
[b] Average of 3 replicates.
[c] Average of 2 replicates.
[d] Between treatment means.
[e] One pot only.

Table V. Average Concentrations of Several Elements in Sweetclover from Soil Limed with Limestone (L) and Slag (S)

(P.p.m. of dry aerial plant material)

Cuttings	Boron L	Boron S	Calcium L	Calcium S	Magnesium L	Magnesium S	Phosphorus L	Phosphorus S	Manganese L	Manganese S	Copper L	Copper S
Norfolk Soil												
1st	29.0	48.5[a]	22030	21070	5370	6670[a]	4880	4900	279.2	298.7	10.83	10.25
2nd	35.7	54.0[a]	26800[a]	21570	6930	9330[a]	5350	5520	231.0	206.8	8.67	7.80
3rd	24.5	32.3[a]	14920	13430	3650	5700[a]	5670	5630	111.8	111.0	8.93	9.25
5th	18.3	21.5	20570	20080	2970	4920[a]	4100	4330	126.8	123.5	10.58	11.48
Fallsington Soil												
1st	52.2	81.3[a]	38970[a]	23480	6570	16030[a]	2720	3050[b]	94.7	392.3[a]	10.75	13.21[a]
2nd	30.2	88.8[a]	32620[a]	20350	3900	10420[a]	2170	2730[b]	77.5	204.8[a]	8.27	11.18[a]
3rd	25.3	56.5[a]	19250[a]	13570	3050	7700[a]	3350	3870	57.0	310.3[a]	10.30	10.77
5th	20.5	•41.8[a]	24900[a]	15520	2920	7480[a]	2350	2520	69.5	163.7[a]	13.10	11.63

[a] Significantly larger, 1% level, than corresponding value for other liming material.
[b] Significantly larger, 5% level, than corresponding value for other liming material.

tained in the slag except calcium. Included in the study were some plant nutrients, not supplied by either liming material, whose uptake could be indirectly affected. The relative effectiveness of slag and limestone for soil liming was also compared. Chemical determinations were by spectrochemical methods.

On Fallsington heavy loam soil slag liming produced crops containing, percentagewise, 2 to 4 times as much manganese, less calcium, and frequently more copper. On this soil and on Norfolk sandy loam soil slag liming produced crops containing up to 2.5 times as much magnesium and significantly more boron. Aluminum, iron, and sodium contents were unaffected within the accuracy of the tests, and those of phosphorus and potassium in only a few comparisons.

Natural growth differences were the main source of error variance for aluminum, boron, manganese, iron, and sodium, but variance between chemical replicates may at times have concealed otherwise significant differences in crop contents of phosphorus, copper, and calcium. Highly significant differences in magnesium contents were shown in spite of relatively large variation between chemical replicates.

As judged by yield and soil pH, the slag was as effective as a liming material on the Norfolk soil as the limestone, but the latter was the more effective on the Fallsington soil.

Nearly all results described in this paper were strongly affected by the type of soil used and it is believed that generalizations as to the relative merits of slag and limestone for liming the soil, as well as their effects on crop composition, should be made with caution until the soil factor is better understood.

Table VI. Values of Variance Ratio: Total Error[a] / Determination Error[b]

Element[c] Determined	Norfolk Soil 1st	Norfolk Soil 2nd	Norfolk Soil 3rd	Norfolk Soil 5th	Fallsington Soil 1st	Fallsington Soil 2nd	Fallsington Soil 3rd	Fallsington Soil 5th
Aluminum	3.36[d]	8.14[d]	5.88[d]	4.58[d]	5.83[d]	3.02[d]	2.75[d]	1.31
Boron	3.32[d]	2.05[d]	2.50[d]	2.61[e]	3.96[d]	4.90[d]	3.31[d]	1.82
Calcium	0.95	2.68[d]	4.28[d]	10.00[d]	0.90	1.20	5.47[d]	0.31
Copper	2.47[d]	0.91	0.84	1.55	1.40	1.58	1.52	1.26
Iron	2.84[d]	16.4[d]	1.20	4.90[d]	5.75[d]	3.00[d]	2.10[e]	2.03
Magnesium	0.65	1.11	3.06[d]	2.48[e]	1.35	3.18[d]	4.16[d]	0.60
Manganese	2.11[d]	1.92[e]	1.59	4.27[d]	2.12[d]	2.30[e]	6.70[d]	1.82
Phosphorus	1.27	2.01[e]	1.90[e]	1.86	4.30[d]	8.85[d]	3.42[d]	1.78
Sodium	2.42[d]	3.55[e]	0.34	3.05[d]	18.08[d]	10.57[d]	47.6[d]	18.3[d]

Values of Ratio for Indicated Soil and Cutting

[a] 22 degrees of freedom; reduced to 11 in 5th cutting.
[b] 108 degrees of freedom in first cutting, 36 in second and third, 24 in fifth cutting.
[c] Calculation could not be made for potassium due to lack of replication in chemical determinations.
[d] Significant, 1%, or higher, level.
[e] Significant, 5% level.

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