THE RELATIVE EFFECT OF LIME AS OXIDE AND CARBONATE ON CERTAIN SOILS.

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IN an earlier communication by one of us (1) an account was given of some preliminary experiments on the action of caustic lime on the soil, with particular reference to the phenomena of partial sterilisation.

From the practical standpoint the question is of considerable importance, inasmuch as an effective sterilising agent for use in intensive field cultivation has yet to be found. Caustic lime, however, has other effects: it is used for promoting more rapid decay, thus ensuring a quicker circulation of foodstuffs in the soil, and employed for destroying soil pests and for "sweetening" soil. Little, however, is known of the mechanisms of these changes, and the present extended investigation was undertaken to study the subject from a broader point of view.

Schulze in 1846 (2) found that an application of caustic lime to a humus soil accelerated the consumption of oxygen and the production of carbon dioxide in a marked degree. Similar results were recorded by Peterson (3) and at a later date and with reference to carbonate, by Ebermayer (4) and also Hilgard (5), while the effect of caustic lime in destroying organic matter of the soil has been demonstrated by Wheeler, Sargent and Hartwell (6) amongst others. Boussingault observed that the conversion of unavailable nitrogen to ammonia was greatly facilitated by applications of lime, while the production of nitrates was inhibited. The type of action on micro-organic growth in

the soil depends largely on the compound added. Calcium oxide not only neutralises soil acidity but also appears to break down some organic compounds and increases the amount of compounds easily resolved into ammonia or capable of serving as food for bacteria. Calcium carbonate, on the other hand, appears only to neutralise acid soil compounds and not to decompose the complex organic residues. This difference accounts for many of the experimental results obtained.

Chester (7) records increases in the number of organisms in certain limed soils, and concludes that this effect was not due to any direct action of the lime but to the more favourable reaction induced in the soil. In field experiments by Fabricius and von Feilitzen (8) an application of lime greatly increased the number of bacteria in moor soils, those in their natural condition containing only relatively few organisms.

Engberding (9) records a temporary rise in the numbers of bacteria following treatment of a soil with 0.1 per cent. calcium oxide. This is in accordance with the results already recorded by us.

Fischer (10) added lime to soils and observed first an appreciable initial depression in the numbers of bacteria and then a rapid rise to very high numbers. This was regarded by the author as a pure stimulation effect, although we consider it was due to the production of available food stuffs by the lime.

Wolf (11) observed the favourable effect of lime on the production of nitrates, and this was confirmed at a later date by Peterson (3) and numerous others. The increased availability of certain fertilisers as the result of liming has been shown to be effected with raw bone by Jenkins and Britton (12) and with dried blood, cotton seed meal and other organic residues by Withers and Fraps (13).

The effect of certain additions of lime on nitrification as also on nitrogen fixation, etc., has been further demonstrated. Wohltmann, Fischer and Schneider (14), examining field soils which had been limed, found that the amount of nitrate and the available potash and phosphate were increased in consequence.

The importance of the presence of lime in the soil for nitrogen fixation has been shown by Ashby, working in this laboratory, who found that a deficiency in this soil constituent led to a decrease in nitrogen-fixing powers, while the susceptibility of the free-living nitrogen-fixing organism *Azotobacter* has been suggested as a test for the presence of alkaline carbonates or calcium carbonate in the soil (15). The function of lime in increasing the biochemical efficiency

of bacteria has been demonstrated in numerous instances by means of the Remy-Löhnis method, and work on these lines has indicated an improvement in soil conditions for such processes as peptone decomposition, nitrification and nitrogen fixation (16).

In the earlier paper, to which reference has already been made, it was shown that lime in the caustic state exerted in common with other mild antiseptics a specific action by disturbing the biological equilibrium in the soil. As a result of this, certain classes of protozoa, in common with the nitrifying bacteria, were destroyed by heavy applications of lime; after an initial depression, the total numbers of bacteria growing on gelatine plates were subsequently largely increased, and led to corresponding increments of ammonia, and, in pot experiments, of plant growth. In continuation of this work we have attempted to determine the amount of lime required to induce partial sterilisation, and the relative values of calcium oxide and carbonate in other and acid soils, and further, to determine the general character of the changes set up in each case.

EXPERIMENTAL.

The investigations were carried out with five soils of widely different types. Their general characters are detailed below and, in some cases, information as to their behaviour towards lime under field conditions is available.

1. *Rothamsted Soil*. This is a poor unmanured soil from the paths on Hoos Field, it is a stiff clay loam overlying chalk and containing 2.22 per cent. carbonate.

2. *Chelsea Soil*. From the Physic Gardens, Chelsea, S.W. This soil was originally Thames Sand, but by heavy applications of stable manure for many generations and by deposition of soot it has become highly organic in character and black in colour.

3. *Craigstone Soil*. From the Experimental Farm of the North of Scotland College of Agriculture. It is a light sandy organic soil deficient in carbonate but regarded as being comparatively fertile.

4. *Millbrook Soil*. From a portion of the Woburn Experimental Fruit Farm. It is a very light sandy soil, low in organic matter, and was selected on this account to indicate how far injurious results might attend heavy dressings of caustic lime.

5. *Woburn Soil*. From the Woburn Experimental Station of the Royal Agricultural Society. The soil is an open sandy loam, and has

been rendered distinctly acid by annual applications of sulphate of ammonia for the last 37 years. This acidity is so pronounced in the field as to check the growth of wheat and barley but not of oats.

TABLE I. *Showing the percentages of organic matter, nitrogen, etc., in the various soils.*

	Loss on ignition	Nitrogen	Carbonate as CaCO ₃	CaO	MgO	Clay
Rothamsted Soil	7.72	0.133	2.66	1.94	0.21	1.39
Millbrook ,,	4.46	0.085	0.03	0.26	0.15	0.59
Chelsea ,,	14.32	0.455	0.89	1.42	0.17	0.63
Craibstone ,,	14.55	0.316	none	0.41	0.22	0.42
Woburn ,,	4.58	0.117	none	0.56	0.15	0.63

In order that the changes following treatment might be determined as closely as possible, monthly examinations of the various soils were carried out. The numbers of bacteria were ascertained by the gelatine plate method, and the presence of protozoa tested by inoculation of a sample of each soil into hay infusion. Free ammonia in the soils was estimated by the method described by Russell¹ and the nitrates determined after reduction by the zinc-copper couple.

Before treatment all the soils were passed through a 3 mm. sieve and filled into bottles in lots of 900 grms. A set of bottles from each soil was set aside as control, and the others received calcium oxide in the proportion of 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0 per cent., while calcium carbonate was added to another lot to the extent of 1 per cent., with the exception of the Craibstone soil, where applications of 0.3, 0.6, 0.9 per cent. of carbonate were made. The water content was made up, by means of sterilised water, to 18 per cent. A set of bottles was taken immediately after the end of this ten day treatment, and the others were stored provided with cotton wool plugs at room temperature.

Rothamsted Soil.

As shown above, this soil already contained sufficient calcium carbonate for normal growth, and further additions fail to induce any change in bacterial growth, production of plant food, or weight of crop. All the applications of quicklime, with the exception of 0.1 per cent., caused an initial depression in the numbers of bacteria. In the case of the lightest application the bacteria rose within the first ten days from

¹ Russell, *This Journal*, 1910, **3**, 233.

23 to 37 millions, and then decreased gradually to the level in the untreated soil. Thirty days afterwards the bacteria in the soil receiving 0·2 per cent. calcium oxide had risen to 166 millions and then began to decrease. Somewhat similar changes occurred in the soils receiving heavier dressings, and in general the heavier the application the greater is the initial depression in bacterial numbers, and the longer the period before the numbers for each particular dressing attain a maximum. The soil receiving 1·0 per cent. of caustic lime showed no material increase in numbers even after 120 days. Further, the addition of a fairly large quantity of carbonate failed to affect the bacterial numbers. The high numbers obtained with some of these soils, for instance after 90 days with 0·5 per cent. of calcium oxide, were chiefly a yellow micro-coccus, which disappeared within a short time and presumably flourished on some of the decomposition products resulting from the action of the lime on the soil.

The direct chemical action of the lime results in an immediate increase in the amount of free ammonia, and especially in the case of the heaviest dressing, where during the period of bacterial inaction the amount of ammonia increased from 3 to 24 parts per million, whilst when the bacteria were active it rose from 24 to 92 parts per million. The very high bacterial numbers observed after 90 days are not, however, associated with any corresponding increase of ammonia; indeed, where 0·5 per cent. of lime was added, no increase was obtained between the 40th and the 120th day. Initial inhibition of nitrification is apparent with dressings above 0·1 per cent. calcium oxide, and permanent inhibition with 0·4 per cent. Tests for protozoa showed the presence of some of the larger forms in the control, and the two soils receiving the lower applications of lime. After 40 days they appeared in soil receiving 0·3 per cent. and were absent from the soils receiving heavier doses, while present in that receiving carbonate.

These two facts indicate that the partial sterilisation effect is produced by dressings of 0·3 per cent. or more calcium oxide. But where a solid and non-volatile antiseptic is employed it is difficult to discriminate sharply between the partial sterilisation and other effects.

Millbrook Soil.

This light sandy soil exhibits a greater sensitiveness towards relatively small applications of caustic lime than the Rothamsted soil. Not only is the initial depression in bacterial numbers greater, but the effect appears to persist longer. With the lighter doses such as 0·1 and

TABLE II. *Showing the effect of calcium oxide and of carbonate on numbers of bacteria and the production of ammonia and nitrate in Rothamsted soil.*

(a) Bacteria											Gain in nitrogen as ammonia and nitrate after 260 days
Treatment	Millions per gram of dry soil after										
	10 days	40 days	60 days	90 days	120 days	160 days	200 days	260 days			
Control soil	23	20	15	17	11	14	7	11			
Soil + 0.1 % CaO	37	32	21	44	18	14	7	13			
Soil + 0.2 "	12	116	49	101	32	73	24	23			
Soil + 0.3 "	6	61	61	104	43	30	42	34			
Soil + 0.4 "	5	32	36	247	100	46	45	75			
Soil + 0.5 "	3	16	41	474	22	24	41	41			
Soil + 1.0 "	2	1	1	3	4	24	72	27			
Soil + 1.0 % CaCO ₃	22	21	18	12	14	10	7	11			

(b) Ammonia and Nitrate														
Treatment	Expressed as parts of nitrogen per million of dry soil										Gain in nitrogen as ammonia and nitrate after 260 days			
	Nitrogen present as ammonia after					Nitrogen present as nitrate after								
	10 days	40 days	60 days	90 days	120 days	200 days	260 days	10 days	40 days	60 days		90 days	120 days	200 days
Control soil	3	2	1	1	3	3	1	11	12	12	13	14	18	24
Soil + 0.1 % CaO	3	2	1	1	2	2	1	11	18	22	24	26	32	33
Soil + 0.2 "	3	11	3	5	3	3	1	10	12	20	29	43	49	56
Soil + 0.3 "	8	15	12	14	12	12	4	9	12	13	11	17	45	48
Soil + 0.4 "	10	16	12	24	30	34	37	11	12	10	9	12	24	19
Soil + 0.5 "	12	26	32	27	25	54	44	11	12	12	10	13	12	17
Soil + 1.0 "	13	20	15	17	25	67	93	17(?)	14	12	14	13	13	13
Soil + 1.0 % CaCO ₃	2	2	2	1	2	2	2	13	16	12	13	16	18	17

0.2 per cent. calcium oxide, however, there is a quick recovery within the first 10 days, and the bacterial content rises to about 77 million. This we suppose to be due to a temporary feeding effect, as is also the high content observed at the end of 30 days with the 0.3 per cent. application. The application of carbonate to this soil, comparatively poor in lime, is not followed by any appreciable increase in the numbers of bacteria for the first few months, although the production of nitrates appears to be increased slightly.

The initial amount of ammonia produced by the action of 0.1 per cent. calcium oxide was almost completely nitrified within the first month, whilst the effect of 0.2 per cent. persisted for a month longer. A greater retardation by 0.3 per cent. persisted up to four months, and at the end of this time nitrification set in. All larger dressings completely inhibited the process; in fact a slight loss of nitrate seems to have occurred. As already pointed out, the effect of the carbonate is slight but definite. Examinations for protozoa after 30 days showed the absence of ciliates from all the soils receiving more than 0.2 per cent. calcium oxide, and of all forms when 0.5 and 1 per cent. were given.

Chelsea Soil.

As compared with the behaviour of the two foregoing poor soils, that of rich soils such as Chelsea, containing an abundance of carbonate, or Craibstone, deficient in carbonate, is very striking. Table IV shows that even the heaviest application of calcium oxide failed to reduce the numbers of bacteria to any great extent in the Chelsea soil. The numbers show considerable variation, but in general they increase up to about 70 days, and then steadily fall off. Finally, after 10 months, they are roughly proportional to the amount of caustic lime applied. Carbonate had little or no effect. No permanent depression of nitrification occurred, the heavy application of 1.0 per cent. calcium oxide only checked it for the period of 130 days. However, examinations for protozoa immediately after treatment failed to reveal the presence of ciliated protozoa in the soils receiving 0.5 and 1.0 per cent. calcium oxide, but after 130 days flagellates only were found in the latter soil, indicating that about this point some measure of partial sterilisation had occurred. In the case of this soil, as in the two preceding ones, we find the usual equal sensitiveness of nitrifying bacteria and of the higher protozoa towards treatment.

TABLE III. *Showing the effect of calcium oxide and of carbonate on numbers of bacteria and the production of ammonia and nitrate in Millbrook soil.*

(a) Bacteria

Treatment	Millions per gram of dry soil after				
	10 days	30 days	70 days	100 days	130 days
Control soil	14	11	10	9	9
Soil + 0.1 % CaO	57	33	30	22	19
Soil + 0.2 "	77	84	114	35	23
Soil + 0.3 "	3	481	107	58	78
Soil + 0.4 "	1	66	98	29	98
Soil + 0.5 "	1	4	—	30	—
Soil + 1.0 "	3	1	1	21	5
Soil + 1.0 % CaCO ₃	14	14	10	10	12

(b) Ammonia and Nitrate

Treatment	Expressed as parts of nitrogen per million of dry soil										Gain in nitrogen as ammonia and nitrate after 130 days
	Nitrogen present as ammonia after					Nitrogen present as nitrate after					
	10 days	30 days	70 days	100 days	130 days	10 days	30 days	70 days	100 days	130 days	
Control soil	2	1	4	3	2	9	10	12	—	13	4
Soil + 0.1 % CaO	7	1	4	3	1	11	19	19	19	28	18
Soil + 0.2 "	12	13	5	4	2	9	10	31	38	38	29
Soil + 0.3 "	10	16	30	28	7	10	10	8	19	36	32
Soil + 0.4 "	10	14	36	48	45	12	10	8	—	6	40
Soil + 0.5 "	11	12	35	53	53	9	10	10	8	6	48
Soil + 1.0 "	17	13	19	28	52	10	11	13	15	8	49
Soil + 1.0 % CaCO ₃	2	1	4	3	2	9	10	17	17	20	11

Craibstone Soil.

In some respects this soil resembles that from Chelsea; both are light, rich in organic matter, and poor in clay, but while the Chelsea soil contains upwards of 1.0 per cent. calcium carbonate the Craibstone soil contains very little.

The remarkable difference is that the smaller applications of lime do not appreciably affect the bacterial numbers, and 1.0 per cent. caused only a small initial depression, which persists for a short period only. In no instance are such high counts recorded as with other soils, and any depression of the higher protozoa appears to pass off within the

first few weeks after treatment. The addition of various amounts of calcium carbonate¹ failed to induce increased growth of bacteria, presumably because there was no disturbance of the equilibrium between these and other organisms. The total flora, on the other hand, appeared to function more efficiently, and there was a greatly increased nitrate production.

The amount of ammonia produced immediately after treatment is not very great, and it usually disappears within 40 days. Only in the case of the 1.0 per cent. oxide application is there any accumulation of ammonia, and this begins to disappear after about 80 days. In spite of the low carbonate content of the untreated soil, nitrification is active from the very first, but is decidedly accelerated by all the lime applications. The relative return of nitrates for equivalent amounts of calcium or oxide of carbonate would appear to be greater with the former within the first 170 days; between this and 380 days the difference becomes eliminated.

Woburn Soil.

The Woburn soil stands out in striking contrast to these. As a result of its previous annual applications of ammonium sulphate it has been depleted of all carbonate, and possesses a well-marked acid reaction.

Table VI shows that no depression in bacterial numbers is produced at the end of 10 days excepting in the soil receiving 1.0 per cent. calcium oxide. The results suggest an almost immediate absorption of all the lower doses of caustic lime, and simultaneous access to nutrients hitherto held out of action by adverse conditions. The application of 0.1 per cent. calcium oxide has sufficed to suspend temporarily the action of these conditions, but at the end of 200 days there is a return in numbers to the level of those in the control soil. The larger dressings apparently give rise to a feeding effect, and very high numbers (906 millions) are obtained after 90 days with soil 0.4 per cent. CaO. Furthermore, the occurrence of greater numbers of bacteria in this soil than in that receiving 0.5 per cent. is due no doubt to the extinction of less resistant but more actively growing bacteria in the latter². With

¹ With this soil the scheme of experiment was varied by applying three different weights of calcium carbonate for purposes of comparison with the caustic lime.

² This would appear to constitute a parallel with effects observed in other work. Treatment of a soil with toluene serves to kill off certain species of bacteria, which when reintroduced to a treated soil give much higher numbers than are observed in toluened soils not reinfected.

TABLE IV. *Showing the effect of calcium oxide and of carbonate on numbers of bacteria and the production of ammonia and nitrate in Chelsea soil.*

(a) Bacteria													
Treatment	Millions per gram of dry soil after								Gain in nitrogen as ammonia and nitrate after 280 days				
	10 days	40 days	70 days	100 days	130 days	160 days	200 days	280 days					
Control soil	11	30	31	17	20	13	16	14					
Soil + 0.1% CaO	9	19	41	19	16	12	15	11					
Soil + 0.2 "	10	27	40	22	28	21	18	16					
Soil + 0.3 "	9	44	80	25	62	25	22	20					
Soil + 0.4 "	7	42	87	60	97	27	32	31					
Soil + 0.5 "	7	43	325	45	66	38	39	50					
Soil + 1.0 "	5	26	225	18	20	49	139	75					
Soil + 1.0% CaCO ₃	9	30	16	16	36	13	13	13					
(b) Ammonia and Nitrate													
Treatment	Expressed as parts of nitrogen per million of dry soil												
	Nitrogen present as ammonia after						Nitrogen present as nitrate after						
	10 days	40 days	70 days	100 days	130 days	280 days	10 days	40 days	70 days	100 days	130 days	280 days	
Control soil	9	6	8	6	7	7	64	69	85	90	96	115	49
Soil + 0.1% CaO	13	4	10	7	6	6	67	65	99	99	102	123	61
Soil + 0.2 "	15	7	8	6	3	7	71	70	95	108	109	132	66
Soil + 0.3 "	15	5	6	6	3	5	56	57	102	115	116	148	80
Soil + 0.4 "	15	5	9	6	5	5	47	69	102	123	122	152	84
Soil + 0.5 "	15	29	11	6	8	6	64	65	110	100	122	166	99
Soil + 1.0 "	27	36	44	54	75	12	57	55	71	74	71	177	116
Soil + 1.0% CaCO ₃	7	2	9	7	5	8	66	69	80	74	101	109	44

the heaviest dressing of caustic lime the depression in numbers persists for upwards of 150 days, but then a progressive increase occurs at least up to the end of 300 days.

The data obtained from the determinations of ammonia are interesting. The initial amount of ammonia is high on account of previous treatment and the acidity of the soil, but in spite of this a slow change to nitrate occurs as well as additional breakdown processes, since the ammonia is reduced by 9 parts per million and the total production

Curve 1. Bacterial numbers in Woburn soil.

of ammonia and nitrate is increased by 40 parts. Small quantities of caustic lime or of carbonate bring about a rapid decrease in the amount of free ammonia, but larger quantities do not. Only the heaviest dressing, however, retarded the change for any considerable time. The total gain in nitrogen, as ammonia and nitrate, is much greater per increment of 0.1 per cent. calcium oxide than in any of the other soils. Ciliates, amoebae and flagellates were found in all the soils excepting that receiving 1.0 per cent. calcium oxide, in which amoebae only were found after 10 days, but at all subsequent examinations only flagellates appeared. Here again parallelism between disappearance of protozoa and of nitrifying organisms occurs.

TABLE V. *Showing the effect of calcium oxide and of carbonate on numbers of bacteria and the production of ammonia and nitrate in Crabstone soil.*

(a) Bacteria												
Treatment	Millions per gram of dry soil after											
	10 days			40 days			80 days			110 days		
	10	40	210	10	40	170	10	40	140	10	40	210
Control soil	14	10	13	12	9	12	12	12	12	12	12	13
Soil + 0.1% CaO	16	32	7	15	8	13	15	13	13	8	7	10
Soil + 0.2 "	13	14	8	15	8	14	14	14	14	6	6	8
Soil + 0.3 "	10	44	7	18	14	14	14	14	14	7	10	13
Soil + 0.4 "	20	53	13	29	17	22	22	16	16	13	20	20
Soil + 0.5 "	11	40	27	51	25	27	27	24	24	41	60	60
Soil + 1.0 "	4	42	41	54	8	16	54	41	60	5	7	7
Soil + 0.3% CaCO ₃	10	14	8	11	8	16	16	5	5	8	12	12
Soil + 0.6 "	11	14	10	10	8	9	10	8	8	12	12	12
Soil + 0.9 "	10	14	11	13	8	11	13	11	11	10	12	12

(b) Ammonia and Nitrate												
Treatment	Expressed as parts of nitrogen per million of dry soil											
	Nitrogen present as ammonia after						Nitrogen present as nitrate after					
	10 days	40 days	80 days	110 days	140 days	170 days	10 days	40 days	80 days	110 days	140 days	170 days
Control soil	2	4	3	5	4	5	21	26	28	34	43	44
Soil + 0.1% CaO	1	3	3	5	2	5	24	31	31	37	40	49
Soil + 0.2 "	1	4	3	5	3	5	25	33	34	42	47	50
Soil + 0.3 "	6	4	2	4	3	4	27	37	38	45	55	64
Soil + 0.4 "	8	4	3	4	3	4	21	43	47	56	53	77
Soil + 0.5 "	9	9	3	5	4	4	23	39	50	67	77	88
Soil + 1.0 "	13	32	55	35	11	4	24	25	27	68	101	151
Soil + 0.3% CaCO ₃	2	1	4	5	2	4	28	30	34	46	44	53
Soil + 0.6 "	1	2	4	4	4	4	32	34	35	45	56	59
Soil + 0.9 "	2	2	4	4	2	4	26	38	38	45	55	66
Gain in nitrogen as ammonia and nitrate after 170 days							67.5	26	44	43	44	26
							90.6	31	49	40	49	31
							95.5	32	50	47	50	32
							100.1	45	55	55	55	45
							115.8	58	77	77	77	58
							136.8	69	88	88	88	69
							210.0	132	151	151	151	132
							—	34	53	44	53	34
							119.0	40	59	56	59	40
							148.1	47	66	55	66	47

Reviewing the foregoing results, it is obvious that the addition of caustic lime to these soils exercised a marked effect on the growth of putrefactive and nitrifying organisms and on soil protozoa. This action leads to a simplification of the soil flora, and in some cases is sufficient to alter the character of the nitrogen compounds available as food for plants, ammonia production being increased and that of nitrates depressed in the primary stages of growth. The increases in total

Curve 2. Ammonia production in Woburn soil.

ammonia and nitrates for each increment of lime show a certain proportionality with the amount applied, but this varies with the character of the reserves of soil nitrogen and the comparative poverty of the soil in carbonate. The Woburn soil is typical of the first case, where considerable reserves are liberated on the application of small doses of lime; with the Craibstone soil the lime is directly absorbed by the soil, and the comparative returns are low. It may be stated, however, as a general average, that the relative return of nitrogen in a form

TABLE VI. *Showing the effect of calcium oxide and of carbonate on numbers of bacteria and the production of ammonia and nitrate in Woburn soil.*

(a) Bacteria

Treatment	Millions per gram of dry soil after								
	10 days	50 days	90 days	120 days	150 days	200 days	232 days	310 days	
Control soil	5	5	4	4	4	4	5	5	
Soil + 0.1 % CaO	6	11	11	9	10	4	5	3	
Soil + 0.2 "	23	78	82	68	73	29	19	13	
Soil + 0.3 "	97	170	170	132	133	106	77	63	
Soil + 0.4 "	151	387	906	345	178	154	87	71	
Soil + 0.5 "	270	281	470	260	247	180	200	77	
Soil + 1.0 "	2	6	6	7	11	176	329	337	
Soil + 1.0 % CaCO ₃	9	18	52	55	40	33	27	11	

(b) Ammonia and Nitrate

Treatment	Expressed as parts of nitrogen per million of dry soil															Gain in nitrogen as ammonia and nitrate after 310 days	
	Nitrogen present as ammonia after						Nitrogen present as nitrate after										
	10 days	50 days	90 days	120 days	150 days	310 days	10 days	50 days	90 days	120 days	150 days	310 days					
Control Soil	19	16	15	11	7	10	5	15	19	23	29	54	40				
Soil + 0.1 % CaO	19	20	8	1	1	3	11	27	34	48	52	79	58				
Soil + 0.2 "	22	27	15	3	1	3	10	23	38	61	67	84	63				
Soil + 0.3 "	25	38	29	2	1	4	12	21	29	66	70	102	82				
Soil + 0.4 "	24	41	42	16	3	5	11	14	21	49	74	111	92				
Soil + 0.5 "	26	44	49	35	25	5	13	12	17	29	48	116	97				
Soil + 1.0 "	26	21	35	44	42	112	12	19	13	14	16	16	104				
Soil + 1.0 % CaCO ₃	20	28	5	2	1	4	9	23	51	60	71	104	84				

available for plants, within the first 8—9 months, is approximately 1 per cent. of the caustic lime applied; details are given in the following table, where the difference in ammonia and nitrate content of the untreated and each of the treated soils is given in terms of increments of 0.1 per cent. calcium oxide. The data for the different soils are not for directly comparable periods, but are the final figures obtained in each case, as given in the detailed ammonia and nitrate tables.

TABLE VII. *Increments of ammonia and nitrate with various applications of lime.*

Treatment	Rothamsted			Millbrook			Chelsea			Craibstone			Woburn		
	Initial	Final	Increment	Initial	Final	Increment	Initial	Final	Increment	Initial	Final	Increment	Initial	Final	Increment
Untreated	14	25	—	11	15	—	73	122	—	23	72	—	24	64	—
0.1 % CaO	14	34	9	18	29	14	80	134	12	25	95	23	30	82	18
0.2 „	13	57	16	21	40	12	86	139	9	26	100	14	32	87	12
0.3 „	17	52	9	20	43	9	71	153	10	33	104	11	37	106	14
0.4 „	21	56	8	22	51	9	62	157	9	29	119	12	35	116	13
0.5 „	23	61	7	20	59	9	89	172	10	32	140	14	39	121	11
1.0 „	30	106	8	27	60	4	84	189	7	37	214	14	38	129	6
1.0 % CaO ₃	15	19	—	11	22	1	73	117	—	28	152	14	29	108	8

As to the fate of the lime added, fresh evidence will be adduced in a later paper to show that even in soils initially rich in carbonate its reappearance as carbonate is a matter of extreme slowness. Hence the determination of carbonate in a soil recently limed would be quite misleading as to conditions obtaining therein.

POT EXPERIMENTS.

These have been carried out with all except the Woburn soil. The soils were passed through a 3 mm. sieve previous to being filled into glazed earthenware pots (the bottom tubulure of which was corked up in order to prevent loss by drainage), and the amount taken was such as to bring the surface of the soil to within an inch or so from the upper rim of the pot. The weight required consequently varied somewhat with the different soils, 9 kg. of Craibstone soil, 8 kg. of Chelsea

soil, 10 kg. of Millbrook soil and 10 kg. of Rothamsted soil¹ being taken. Lime as oxide and carbonate was applied in the same ratio as in the laboratory experiments. The surface soil was then wetted with 100 c.c. of water in order to allow of efficient action of the caustic lime before it became carbonated. Ten barley seeds were sown in each pot, and after about a month the plants were thinned out to five per pot. Equal numbers of the seedlings were weighed to ascertain the initial effect of the lime on plant growth.

Rothamsted Soil.

The soil was treated on Jan. 15th, 1913, and the barley sown on April 11th; the seedlings were thinned out on May 15th, and the crop, cut on July 15th, was slightly, but as far as could be judged, evenly damaged by birds. Germination in all the soils was regular, but at the time of thinning, those plants in soils with 0·1 and 0·2 per cent. calcium oxide were slightly better than those in the control soil. The higher, especially the highest dressings of oxide, appeared to be injuring growth, causing the tips of the leaves to wither.

Table VIII shows the yields of dry produce, etc. A second crop of mustard was then grown in all the pots, and harvested on Oct. 2nd. The yields of dry matter were greatly increased by the applications of small dressings of caustic lime, and reached a maximum with 0·3 per cent. The next higher dressing caused a slight decrease, while the crop growing in soil with 1·0 per cent. oxide was only 14·0 per cent. of that in the control soil. The addition of carbonate was without effect. The second crop, mustard, showed on the whole progressive increases up to the heaviest lime dressing, and carbonate also appeared to cause a slight increase. The production of dry matter in the two crops also increases to the 0·3 per cent. application, and then declines. The percentages of nitrogen in the dry matter increase with the lime dressings, indicating non-nitric nutrition of the plants. The total nitrogen in both crops shows a steady increase, and not a decrease, with higher lime dressings.

¹ For this soil results showing the effects of lime on plant growth in pot culture and in the field are available elsewhere. Voelcker, J. A., "Annual Reports of the Consulting Chemist." *Journ. Roy. Agric. Soc.* 1898—1913.

On account of its stiff clayey nature the Rothamsted soil was mixed with one-third of its weight of clean sand. The dressings of lime were however calculated on the basis of soil only 1, 3, 7, 5 Ko.

Millbrook Soil.

The pots in this set were put up and the soil treated on March 17th, the barley being sown on May 2nd and afterwards thinned out in the usual way. Germination was good in all cases, with the exception of the heaviest limed soil (Plate IX, figs. 1 and 2). The results are very similar to those described above, except for the greater sensitiveness towards higher doses of caustic lime. A maximum is reached with 0·3 per cent. oxide, while 1·0 per cent. almost checks growth completely. The recovery in the second crop is almost complete, soils with 1·0 per cent. oxide showing a decrease as compared with those receiving the next lower dressing. In some cases the physical condition of the Millbrook soil was altered to such an extent by liming that the seedlings of the first crop were suffering from lack of water, while the soil 10 to 12 inches below was waterlogged.

Craibstone Soil.

The soil was treated and filled into pots on Jan. 16th and barley sown on April 11th. No differences in germination between the various sets could be detected, and the weights of the seedlings removed at the time of thinning, a month later, show decided increases in weight in all cases as compared with the control. Growth was vigorous throughout, and the crop was cut on July 15th. Progressively increasing yields of dry matter were obtained in all cases in the first and second crop, and the beneficial effect of carbonate is well marked. The magnitude of the crops and the nitrogen content, obtained with dressings of 0·1 to 0·3 per cent. calcium oxide, are very similar to those obtained with carbonate. Comparable results are also found in the case of the second crop.

Chelsea Soil.

The soil was treated on March 3rd and sown with barley on May 2nd. Germination was quite even, and the weights of seedlings at the time of thinning, on May 27th, showed slight increases, with the exception of those from soils receiving 1·0 per cent. oxide and 1·0 per cent. carbonate. The crop results are similar to those obtained previously with garden soil¹ (Plate X, figs. 1 and 2). 0·2 per cent. calcium oxide slightly increases the yield, but higher doses tend to decrease it. This is not due to the persistence of caustic lime; indeed lime disappears more rapidly from this soil than from the lighter ones, as is also

¹ Hutchinson, *loc. cit.* p. 327.

Fig. 1. First crop, Barley.

Fig. 2. Second crop, Mustard.

Experiments on the action of Caustic Lime and Carbonate on Millbrook Soil. Treatment (from left to right). Untreated soil, and soil with the addition of 0.1, 0.2, 0.3, 0.5 and 1.0 per cent. caustic lime and 1.0 per cent. chalk respectively.

Fig. 1. First crop, Barley.

Fig. 2. Second crop, Mustard.

Experiments on the action of Caustic Lime and Carbonate on Chelsea Soil. Treatment (from left to right). Untreated soil, and soil with the addition of 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0 per cent. caustic lime and 1.0 per cent. chalk respectively.

TABLE VIII. *Showing the results of pot experiments with various untreated and limed soils.*

Soil and Treatment	1st crop Barley				2nd crop Mustard				Total dry matter in both crops, grams	Total nitrogen in both crops, grams
	Dry matter grams	Relative weights	Nitrogen in crop per cent.	Total nitro- gen in crop grams	Dry matter grams	Relative weights	Nitrogen in crop per cent.	Total nitro- gen in crop grams		
Rothamsted										
Control	7.6	100	0.702	0.049	1.6	100	1.686	0.025	9.2	0.074
Soil + 0.1 % CaO	15.9	209	0.803	0.117	1.3	79	1.785	0.021	17.2	0.138
Soil + 0.2 „	17.0	224	0.925	0.147	2.5	155	1.570	0.037	19.5	0.184
Soil + 0.3 „	22.9	300	1.021	0.217	3.1	190	1.643	0.048	26.0	0.265
Soil + 0.4 „	20.7	276	1.183	0.227	4.0	245	1.769	0.066	24.7	0.293
Soil + 0.5 „	15.1	199	1.802	0.253	7.1	435	1.778	0.119	22.2	0.372
Soil + 1.0 „	1.0	14	3.586	0.034	17.7	1086	3.206	0.531	18.7	0.565
Soil + 1.0 % CaCO ₃	7.6	101	0.641	0.046	1.9	118	1.533	0.027	9.5	0.073
Millbrook										
Control	8.3	100	0.826	0.065	1.7	100	1.979	0.032	10.0	0.097
Soil + 0.1 % CaO	15.3	184	0.942	0.138	1.1	64	1.918	0.020	16.4	0.158
Soil + 0.2 „	19.1	230	1.235	0.225	2.9	171	1.744	0.049	22.0	0.274
Soil + 0.3 „	22.5	271	1.523	0.327	5.3	306	1.560	0.077	27.8	0.404
Soil + 0.5 „	7.1	85	3.678	0.272	15.3	890	2.036	0.295	22.4	0.567
Soil + 1.0 „	0.4	1.5	4.019	0.015	12.0	697	3.227	0.366	12.4	0.381
Soil + 1.0 % CaCO ₃	9.5	114	0.831	0.074	1.1	64	1.802	0.018	10.6	0.092
Craibstone										
Control	28.1	100	0.761	0.202	1.2	100	2.338	0.026	29.3	0.228
Soil + 0.1 % CaO	27.0	96	0.680	0.172	1.9	154	1.835	0.032	28.9	0.204
Soil + 0.2 „	30.9	110	0.652	0.192	1.8	148	2.071	0.036	32.7	0.228
Soil + 0.3 „	32.6	116	0.754	0.231	2.6	210	2.048	0.049	35.2	0.280
Soil + 0.4 „	37.3	132	0.872	0.305	3.6	295	2.260	0.076	40.9	0.381
Soil + 0.5 „	37.9	135	1.014	0.360	4.4	362	2.100	0.087	42.3	0.447
Soil + 1.0 „	45.0	160	1.544	0.637	8.0	654	2.246	0.168	53.0	0.805
Soil + 1.0 % CaCO ₃	33.2	118	0.762	0.237	3.8	309	1.965	0.069	37.0	0.306
Chelsen										
Control	34.7	100	1.242	0.405	2.9	100	1.855	0.050	37.6	0.455
Soil + 0.1 % CaO	34.2	98	1.192	0.384	3.5	122	1.783	0.057	37.7	0.441
Soil + 0.2 „	39.9	115	1.254	0.470	3.9	135	1.784	0.066	43.8	0.536
Soil + 0.3 „	39.1	112	1.398	0.509	3.8	133	1.812	0.064	42.9	0.573
Soil + 0.4 „	38.4	111	1.689	0.614	5.4	190	1.658	0.084	43.8	0.698
Soil + 0.5 „	36.4	105	1.989	0.694	6.7	234	1.722	0.108	43.1	0.802
Soil + 1.0 „	32.6	94	2.495	0.668	16.5	572	2.307	0.364	49.1	1.032
Soil + 1.0 % CaCO ₃	33.3	96	1.061	0.338	3.5	122	1.659	0.054	36.8	0.392

indicated by the relatively short period during which nitrification is inhibited. The ammonia and nitrate figures show a steady increase with these doses, so that the crop depression appears to be a physiological effect on the plant rather than a shortage of food¹. Throughout the period of growth of the first crop, the barley plants appeared very flaccid in character; this effect was also evident in the third crop which was rye.

The second crop, mustard, does not show this effect, but gives a steady rise with increasing lime applications. In general, there is no such increased nitrogen content in plants growing in these limed soils, as was observed with the Rothamsted and Millbrook soils.

SUMMARY.

Caustic lime is found to have two distinct effects on the soil:

1. A partial sterilisation effect,
2. A chemical action, decomposing some of the soil organic matter.

The amount of caustic lime necessary to induce specific changes in the flora and fauna of the soil depends very largely on the character of the soil. The light sandy Millbrook soil, poor in organic matter and in carbonate, reacted sharply with 0·2 to 0·3 per cent. caustic lime; the Rothamsted clay soil, poor in organic matter but rich in carbonate, was found to react to 0·3 to 0·4 per cent.; the acid Woburn soil required an amount between 0·5 and 1·0 per cent., as did also the rich Chelsea garden soil, which already contained carbonate; the Craibstone soil, with a high organic and a low carbonate content, failed to react even to applications of 1·0 per cent. caustic lime.

Each of these soils, as well as many others examined, appears to absorb directly a definite amount of caustic lime, and until these requirements are fully satisfied the partial sterilisation phenomena do not set in. These phenomena include a sudden initial decrease and subsequent increase in the numbers of bacteria, the extinction of the larger forms of protozoa and the inhibition of nitrate production. Lower doses than those required for partial sterilisation induce a temporary suspension of nitrification, and consequent accumulation of ammonia, for periods varying with the amount of lime and the character of each soil; they also lead to a temporary increase in numbers of

¹ In a parallel case of peaty soils Ritter (17) suggested that the injurious effect occasionally obtained on liming may be due to oxalic acid produced, and Densch (18) suggests a reduction of nitrates to nitrites.

bacteria capable of growing on gelatine plates, but these afterwards decrease until the level of the untreated soil is reached.

Caustic lime chemically breaks down some of the organic matter of the soil, as shown by the ammonia formed during periods when soil bacteria are quiescent; when, however, bacterial growth commences, there is a large increase in the rate of ammonia production.

The return in nitrogen, as ammonia and nitrate for each increment of lime applied, varies with the character and reaction of the soil and the carbonate content. On the average, and within a period of about 250 days, it amounted approximately to 1.0 per cent. by weight of the caustic lime applied. Carbonate gave less returns, apparently because of its relative inaction on soil organic matter.

The pot experiments show amounts of available nitrogen in the soils comparable with the amounts of ammonia and nitrate produced in the laboratory experiments. In some cases the amount of caustic lime applied was sufficiently large to check the growth of bacteria and to depress plant growth in the first crop¹, but in the case of the Chelsea soil the bacteria were active but plant growth was depressed, a phenomenon not yet satisfactorily explained.

As in other experiments, inhibition of nitrification resulting from applications of lime leads to a higher nitrogen content in the plants. This has been ascribed to the assimilation of nitrogen compounds other than nitrates, and, if occurring to any extent, involves an uneconomic utilisation of soil nitrogen. Where the amount of lime does not check nitrification, as in the case of the lighter dressings to the Craibstone soil, the nitrogen content of the plants is about the normal.

¹ A certain agreement exists between maximum yields of first crop with applications of caustic lime sufficient to induce partial sterilisation (*e.g.* Millbrook and Rothamsted soils).

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