EXCHANGEABLE SODIUM AND THE PHYSICAL PROPERTIES OF SOILS.

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SUMMARY.

1. The chemical effect of an irrigation water upon a soil is shown to depend primarily on the $\frac{Ca + Mg}{Na + K}$ *value of the water, to a less extent on the total solids and the duty of water, and not at all on the previous irrigation history of the soil.*

2. The conditions for the entry of sodium into the exchange complex of irrigated soils are defined.

3. It is shown that free alkali (sodium bicarbonate) in an irrigation water has no particular activity ascribable to it except so far as it furnishes sodium ions.

4. The physical properties of a soil are not adversely affected by exchangeable sodium until it constitutes about 15 per cent. of the total exchangeable bases. The deterioration is then rapid as sodium increases.

5. The Keen-Raczkowski test, a simple percolation experiment, and a simple penetrometer were used to measure the physical degeneration of soils due to excess sodium.

6. Laboratory tests suggest that cultivation, particularly when the soil is dry, is more likely to be responsible for inducing bad physical characteristics in Burdekin soils that is salt accumulation resulting from saline irrigation waters. In each event the water-holding capacity of the soil, its air supply and its permeability are reduced; its hardness on setting is increased.

7. The natural waters of the Queensland coastal belt, having a rather low Figure of Merit as irrigation waters, need to be chosen with care in order to avoid puddled soils.

Introduction.

In assessing the suitability of a water for irrigation purposes it has been customary to accept a set of limiting values for the concentrations of salt, free alkali, or total solids. These limits have been fixed somewhat arbitrarily from general experience, but this method is unreliable and does not enable accurate conclusions to be drawn as to possible deleterious effects of a given water on the soil and therefore on crops.

The writer has used a different criterion for this purpose, and, as will be shown in the paper, it enables the true action of the water on the soil to be predicted with some certainty. This criterion, which has been termed the "Figure of Merit" of the water, is simply the ratio of the divalent ions calcium and magnesium to be monovalent ions sodium and potassium present in the water, all expressed as chemical equivalents. If thus takes cognizance of the reversible nature of the base exchange reaction which occurs when the soil is irrigated. The alkalis (almost entirely sodium in a natural water) tend to produce a sodium soil by displacing calcium and magnesium from the soil: but this action is resisted by the divalent ions already present in the water. The state of equilibrium which is attained depends on the Figure of Merit of the water, and to a much smaller degree on the amount and kind of replaceable bases in the soil and the total weight of saline matter introduced by irrigation. This Figure of Merit (which will be referred to in this paper as f) is thus $\frac{Ca + Mg}{Na + K}$ and has previously been used by the writer (Cassidy, 1937, 1944) in surveys of the waters of the Queensland coastal belt.

Admittedly there are factors to be considered other than the effect of the water upon the soil: the tolerance of the plant to high osmotic pressures, the water-holding capacity of the soil, and the permeability of the soil to water, are all of vital concern. In the final analysis, however, these particular factors reduce to the same thing—the ability of the plant to tolerate the concentration of soluble salts that may be established in the soil—and this topic is not the concern of the present paper.

Laboratory Experiments.

The foregoing discussion has anticipated the results of experiments which were conducted to find the effect of salinity of various degrees and kinds upon the chemical composition of the soil. In a few cases field observations were utilized; here the effect of irrigation waters was gauged by the difference in composition evidenced in their drainage, or by analysing soil samples from two fields of the same soil before and after these fields had been subjected to irrigation waters of different composition. Generally, however, laboratory experiments were conducted in which a column of soil contained in a glass cylinder fitted with a cotton-wool filtering plug was leached slowly by either a natural or a synthetic irrigation water. The soil columns were usually about three or four inches long and the cylinders either two or three and a-half inches in diameter. In a few instances narrower cylinders and smaller amounts of soil were used. Leaching times were of the order of one acre-inch per hour, with a free drainage period overnight. After leaching, the soils were washed free of salts with 70 per cent. alcohol, air-dried, and replaceable bases determined. For this estimation a portion was extracted by continued leaching with 0·02N HCl and the various ions determined as described elsewhere (Cassidy, 1944).

In Table 1 are given details of the leaching solutions used in the laboratory experiments. The ionic concentrations are expressed as milliequivalents per litre; from these the f value and the ratio of calcium to magnesium have been calculated. Finally, the total salt concentration has been given in terms of grains per Imperial gallon, since this unit is used by many workers, and where free alkali (sodium bicarbonate) is present the amount has been

Table 1.

ANALYSIS OF LEACHING SOLUTIONS USED.

Leaching Solution.	HCO_3	Cl	SO_4	Fe	Ca	Mg	Na	K	Total. cations.	Ca/Mg	$\frac{Ca+Mg}{Na+K}$	Total Solids. (Grains per Gallon.)
	(milli-equivalents per litre.)											
1. Irrigation Water—B. Tapiolas . .	1·38	2·99	5·91	0·11	2·37	2·84	4·71	0·09	10·2	0·8	1·08	45
2. Synthetic	1·47	2·60	1·47	. .	0·49	1·14	3·91	. .	5·6	0·4	0·42	25
3. Synthetic—high alkali	3·59	1·79	0·60	0·07	0·59	0·00	5·31	. .	6·0	. . .	0·11	30, including 11 gr. p.g. free alkali.
4. Synthetic—high alkali	3·41	3·26	Nil	. .	0·46	0·22	6·00	. .	6·7	2·0	0·11	33, including 10 gr. p.g. free alkali.
5. Synthetic—high alkali	3·70	2·51	Nil	. .	0·26	0·13	5·84	. .	6·2	2·0	0·07	30, including 12 gr. p.g. free alkali.
6. Synthetic—high salt	Nil	27·0	Nil	. .	1·62	0·81	24·6	. .	27·0	2·0	0·10	120
7. Brine	Nil	1,000	Nil	. .	Nil	Nil	1,000	. .	1,000	. .	0·00	4,000
8. Synthetic—high salt	Nil	27·0	Nil	. .	1·58	0·78	24·1	(H) 0·54	27·0	2·0	0·10	100 (acid) ; pH about 3.
9. Synthetic—very high salt . .	Nil	57·6	Nil	. .	3·40	1·69	52·0	0·54	57·6	2·0	0·10	230 (acid) ; pH about 3.
10. Equivalent of diluted seawater	Nil	25·5	3·0	. .	0·8	5·0	21·6	(K) Nil	28·0	0·16	0·27	113
11. Synthetic—very high alkali . .	6·6	Nil	Nil	. .	0·2	2·3	4·28	Nil	6·7	1·9	0·64	32, including 23 gr. p.g. free alkali.
12. Synthetic—high salt	Nil	25·1	4·2	. .	7·35	7·35	14·2	0·2	29·2	1·0	1·02	112

Table 2.

DESCRIPTION OF SOILS USED IN LABORATORY EXPERIMENTS.

Soil.	Texture.	pH	Replaceable Bases. (m.e. per 100 g.)					Mechanical Analysis. (per cent.)			
			Ca	Mg	Na	K	Total.	Coarse Sand.	Fine Sand.	Silt.	Clay.
Burdekin Alluvial . .	Dark grey silty clay loam	6·16	14·6	6·5	0·88	0·71	22·7	13·9	40·6	20·9	24·6
Bellenden-Ker Alluvial	Yellowish brown silty loam	6·08	4·72	1·10	0·36	0·61	6·8	8·0	37·6	23·9	30·5
Bundaberg Red Forest	Red sandy loam . .	6·12	3·82	1·18	0·12	0·28	5·4	31·6	24·2	14·1	30·1

shown in the same units. The normal range of medium to high salinity encountered in irrigation waters is covered in Table 1, and waters of moderately high content of sodium bicarbonate are represented. A brine and two acid salty waters are also included. Water No. 10 is a representation of sea water diluted 20 times.

Two Burdekin soils, one a cultivated silty loam from B. Tapiolas and the other an adjacent virgin soil from Christofides and Kallas, were the soils principally used; a Bellenden-Ker alluvial and a Bundaberg red forest soil were also included in some of the experiments. The soils are described in Table 2.

Measure of the Change.—As a measure of the change produced in the soil it is better to express each exchangeable ion as a percentage of the total replaceable bases than as an absolute value. In this way it is possible to deal with the reactive part of the soil only and to minimise the effect of having included a greater or smaller amount of the sand fractions in the particular sample. Small changes in the total exchange capacity of the soil are likewise neutralized, whilst direct comparison between different soils is possible. The criterion chosen has been in all cases Na, and not Na + K, as percentage of total bases, since irrigation waters contain negligible amounts of K, precluding large increases of exchangeable K; moreover, in comparisons of virgin and cultivated soil K changes independently by virtue of its being an important plant food.

Results.—Table 3 presents the effects which the various irrigation waters had on the several soils used. It appears that under the conditions of the experiment 30 acre-inches of water were sufficient to produce most of the ultimate effect obtainable (see trials h and i). In the cases where only 20-25 acre-inches of leachate were used, the narrow cylinders and smaller amounts of soil employed probably gave as complete a state of equilibrium.

A study of Table 3 shows that the f value is the dominating factor determining the chemical status of the soil after leaching. Thus tests a and b indicate that the f values of the waters, and not the amounts of total solids, have determined the exchangeable sodium in the resulting soils when each received a 72 acre-inch application.

The actual effect of free alkali upon the soil is also made clearer. It has often been assumed that even a small amount of free alkali must be injurious in an irrigation water, and in a general way the effect of free alkali has been assumed to be four or five times as great as that of common salt. That these assumptions are not valid for the present enquiry is shown by the data now available. The results show that, with similar values of f and total solids, the higher the free alkali content the greater will be the absorption of sodium by the soil (see tests d, c and e). For waters with similar total solids content but different values of f (see tests l and e), the one with the higher f value has resulted in less sodium absorption by the soil than the other, even though the former contained double the free alkali content of the latter. Results of tests b and l corroborate this.

Table 3.

EFFECT OF IRRIGATION WATER UPON SOIL—LABORATORY EXPERIMENT.

Test.	Soil.	Leaching Solution.	Type of Irrigation Water.				Acre-in. Watering.	Resulting Soil. Replaceable Bases. (Per Cent. of Total.)				Change Produced. Replaceable Bases. (m.e. per 100 g.)		Designation of Resulting Soils.
			$\frac{Ca+Mg}{Na+K}$	Ca/Mg	Total Solids.	Free Alkali.		Ca	Mg	Na	K	Na	K	
					gr. p.g.	gr. p.g.								
	Burdekin Alluvial—													
..	B. Tapiolas, Ayr	..	..	..	..	..	Nil	64·1	29·8	4·3	1·8	..	..	Cultivated soil
a	Ditto	1	1·08	0·8	45	Nil	72	59·2	34·6	4·5	1·7	+0·12	..	..
b	Ditto	2	0·42	0·4	25	Nil	72	59·2	34·0	5·2	1·6	+0·30	..	..
c	Ditto	3	0·11	..	30	11	78	59·0	28·4	10·9	1·7	+1·55	..	..
..	Christofides and Kallas, Ayr	..	..	..	..	..	Nil	64·4	28·6	3·9	3·1	..	..	Virgin soil
d	Ditto	4	0·11	2·0	33	10	32	62·3	27·2	8·3	2·2	+1·06	−0·20	Soil E
e	Ditto	5	0·07	2·0	30	12	37	60·5	25·2	12·0	2·3	+2·16	−0·15	Soil C
f	Ditto	6	0·10	2·0	120	Nil	29	56·6	24·8	16·5	2·1	+3·18	−0·22	Soil D
g	Ditto	7	0·00	..	4,000	Nil	35	11·9	2·8	84·9	0·4	+17·0	−0·68	Soil F
h	Ditto	8	0·10	2·0	100	Acid	31	59·3	23·8	15·8	1·1	+2·99	..	Soil B_1
i	Ditto	8	0·10	2·0	100	Acid	67	58·5	23·2	16·8	1·5	+3·03	−0·38	Soil A
j	Ditto (Soil B_1) ..	9	0·10	2·0	230	Nil	37	60·0	17·3	21·4	1·3	+3·50	−0·46	Soil B_2
k	Christofides and Kallas, Ayr	10	0·27	0·16	100	Nil	20	54·2	35·2	9·2	1·4	+0·96	−0·42	Soil IA
l	Ditto	11	0·64	1·9	32	23	25	60·6	31·7	5·4	2·2	+0·30	−0·24	Soil IB
..	Bellenden-Ker Alluvial ..	..	..	..	Nil	..	..	70·4	16·4	5·4	7·8	..	..	Soil II
m	Ditto	10	0·27	0·16	100	Nil	20	34·4	41·8	18·4	5·4	+0·92	−0·14	Soil IIA
n	Ditto	11	0·64	1·9	32	23	25	52·0	29·2	12·4	6·4	+0·69	+0·02	Soil IIB
..	Bundaberg Red Forest ..	..	..	..	Nil	..	..	70·7	21·9	2·2	5·2	..	..	Soil III
o	Ditto	10	0·27	0·16	100	Nil	20	39·0	44·8	14·9	1·2	+0·72	−0·21	Soil IIIA
p	Ditto	11	0·64	1·9	32	23	25	49·2	39·3	9·1	2·4	+0·64	−0·08	Soil IIIB

The reaction of a water *per se* is of no consequence, since tests f, h and i show the effect at constant value of f = 0·1 of a neutral water compared with two that were slightly acid with HCl. Obviously only acid water that was buffered would exercise any effect. The bad effect of a purely saline water is shown by test g.

It is to be noted that the waters listed in Table 1 cover the types actually encountered in practice and described by Cassidy (1937, 1944) first for the Burdekin delta and since for the Queensland coastal region generally. A large number of analyses has indicated that very saline and very alkaline waters both have an f value as low as 0·5 and often much lower. It is this low value which causes degradation of the soil; for the low figure is the result of there being insufficient calcium and magnesium to offset the effect of the large amount of sodium chloride or the relatively large amount of sodium bicarbonate present in such waters.

A further conclusion to be drawn from Table 3 is that different soils react differently to the same water; those with high base exchange capacity resist change to a greater extent than do lighter soils. Such buffer action is the consequence of the greater number of ions which a soil of high exchange capacity can furnish to produce the reverse base exchange reaction. Thus it will be observed that waters 10 and 11 cause a smaller percentage saturation with sodium in the Burdekin soil (22 m.e. total bases) than in the Bellenden-Ker and Bundaberg soils, which have only seven milliequivalents and six milliequivalents respectively.

Field Results.

It now remains to examine the field evidence bearing upon these laboratory studies. The available data are collected in Table 4. From cases 11 and 12 representing adjacent farms the f value of the irrigation water is again seen to be the controlling factor in the entry of exchangeable sodium into the soil. In any case it is clear that a concentration of up to 54 grains per gallon of total solids had no very harmful effect on Ayr soils when the f value was greater than unity. The experience at Giru, a district near Ayr which lacks good irrigation water, shows a definite ingress of sodium ions due to an f value of 0·32 at 122 grains per gallon total solids (see soils 6 and 8). This conclusion was arrived at after allowing for soluble salt and calcium carbonate which were present in the soil. Even a two-inch irrigation at an f value of 0·2 has caused an increase in the small amount of exchangeable sodium originally present. The four soils from the Seaforth area of the Burdekin district provide an interesting series. Tapiolas's soil has apparently not increased in exchangeable sodium after many years of irrigated cultivation whereas Cabassi's soil shows considerable deterioration due to a low f value with 135 grains per gallon total solids. The high replaceable sodium in the Kalamia Estates soil is rather surprising if the most recent water analysis represents irrigation actually applied; but previous samples analysed have exhibited a lower f value.

Table

EFFECT OF IRRIGATION WATER

Soil No.	Soil.	Type of Irrigation Water.				Acre-inch Watering
		$\frac{Ca+Mg}{Na+K}$	Ca/Mg	Total Solids.	Free Alkali.	
				gr. p.g.	gr. p.g.	
1	J. Guy, Klondyke, Ayr	1·67	. .	17	1	+
2	Ditto	0·84	. .	24	7	20
3	D. Tooney, Klondyke, Ayr	1·67	. .	17	1	. .
4	Ditto	1·35	. .	54	Nil	. .
5	Cyprus Farming Co., Home Hill	0·6	1·2	60–200	Nil	+
6	J. L. Humphry, Giru	. .	. .	Nil	. .	Nil
7	Ditto	0·2	. .	80	4	2
8	Ditto	0·32	. .	122	Nil	25
9	Christofides and Kallas, Seaforth, Ayr . .	. .	. .	Nil	. .	. .
10	Kalamia Estate, Seaforth, Ayr	0·1	. .	95	Nil	. .
11	Cabassi Bros., Seaforth, Ayr	0·14	. .	135	9	. .
12	B. Tapiolas, Seaforth, Ayr	1·08	0·8	45	Nil	. .
13	Ditto (Drainage Water) . .	0·87	1·0	. .	. .	. .
14	F. Clarke and Sons, Seaforth, Ayr	0·73	0·75	30	Nil	. .
15	Ditto (Drainage Water) . .	1·0	0·67	. .	. .	. .
16	W. Pearce, McDesme, Ayr	0·78	. .	9	3	+
17	Ditto	0·18	. .	38	29	30
18	G. Fordyce, Mackay	0·08	1·3	. .	. .	. .
19	Ditto	. .	. .	Nil	. .	Nil
20	Ditto	. .	. .	. .	. .	. .
21	Ditto	. .	. .	. .	. .	. .
22	Newlands Field Station, Nevada, U.S.A.* . .	1·03	33·6	15	. .	. .
23	Ditto*	. .	. .	. .	. .	. .
24	Ditto (Drainage water)*	0·38	26·8	30–45	. .	. .
25	Ditto (Subsoil water)* . .	0·18	. .	75–90	. .	. .
26	Mediterranean Loess Soil†	. .	. .	Nil	. .	. .
27	Ditto†	0·40	1·33	538	. .	. .
28	Californian Soil‡	0·20	1·8	60	. .	. .
29	Ditto‡	1·9	1·0	130	. .	. .

* Schofield, Moon, and Knight, 1936. † Puffeles, 1939. ‡ Eaton, 1935.

4.

upon Soil—Field Results.

Replaceable Bases in the Soil.								Remarks.
Ca	Mg	Na	K	Ca	Mg	Na	K	
m.e. per 100 g.				Per Cent of Total.				
15·6	4·0	0·57	0·57	75·3	19·3	2·7	2·7	+ A few years.
13·0	3·9	1·09	0·85	68·9	20·7	5·9	4·5	
18·2	6·5	1·00	0·47	69·6	24·8	3·8	1·8	
17·6	8·6	1·38	0·37	63·0	30·8	4·9	1·3	
..	..	..	..	60·8	30·0	7·4	1·8	+Several years.
19·8	..	0·28	..	..	..	..	..	No irrigation.
16·7	..	0·96	..	..	..	..	..	
+22·2	..	++5·41	..	..	..	..	..	+Includes 2 m.e. $CaCO_3$ ++2·6 m.e. Cl present.
14·6	6·5	0·88	0·71	64·4	28·6	3·9	3·1	No irrigation. Virgin soil.
12·3	8·2	3·08	0·28	51·7	34·2	12·9	1·2	
14·0	7·4	3·72	0·79	53·8	28·8	14·4	3·0	
..	..	..	..	64·1	29·8	4·3	1·8	
..	..	..	..	..	..	..	..	
..	..	..	..	..	..	..	..	
..	..	..	..	..	..	..	..	Adjusted for $CaSO_4$ taken from soil.
19·6	5·8	0·46	0·52	74·2	22·0	1·8	2·0	+A few years.
23·8	7·4	0·93	0·47	72·9	22·8	2·9	1·4	
..	..	..	..	..	..	..	..	Salt incrustation left by spring.
..	..	..	..	71·5	26·0	2·1	0·4	Normal soil ; not watered by spring.
..	..	..	..	50·2	31·5	17·5	0·8	Soil from affected area.
..	..	..	..	30·5	21·5	48·0	..	Soil from incrustation.
..	..	..	..	..	..	..	..	Either Ca and Mg have been given up by the water, or Na and K have been taken from the soil.
..	..	..	..	..	..	..	..	
..	..	..	..	..	..	..	..	
..	..	..	..	80·6	13·1	1·8	4·5	Original soil.
..	..	..	..	35·0	8·7	54·8	1·5	Permeability reduced to one-seventh of original.
..	..	..	..	..	..	..	..	In 9 years a pervious and highly productive soil was rendered impervious and unable to produce lucerne.
..	..	..	..	..	..	..	..	Lucerne and cereals still growing well after 18 years using this water.

The aggravating effect of high total salinity in addition to an unfavourable $\frac{\mathrm{Ca}+\mathrm{Mg}}{\mathrm{Na}+\mathrm{K}}$ ratio has been noted by Eaton (1935) and by Kelley, Brown and Liebig (1940). Data given by the latter authors appear to show that at their $^{\mathrm{Ca}}/_{\mathrm{Na}}$ ratio of 0·25 no entry of sodium occurs unless the total solids exceed 400 grains per gallon. However, these authors favour a ratio of unity as more desirable.

When the drainage water from a soil has a lower f value than the original irrigation water, a replacement from the soil of monovalent by divalent cations is indicated. Conversely, an increase in the f value of a water, whilst passing through a soil, indicates absorption of monovalent (sodium) ions by the soil with consequent deterioration of its structure. The previous indication that Tapliolas's soil has not been undergoing salt damage is borne out by the composition of the drainage water. This showed a tendency to an increase in monovalent and a decrease in divalent cations; meanwhile the unchanged chloride content proved that no concentration of the water had taken place. The small increase found in the sulphate content indicated that some soluble sulphate had been taken up from the soil. Of these data, only the f value and the $^{\mathrm{Ca}}/_{\mathrm{Mg}}$ ratio are shown in the table. The drainage water from F. Clarke & Sons had become concentrated to about twice the original value; when this was allowed for it was found that equivalent amounts of calcium and sulphate (obviously dissolved salts) had been taken from the soil. Making due allowance for this water-soluble calcium, the usual ratios were calculated and showed that the soil had possibly suffered some deterioration. The data of W. Pearce presents a definite anomaly. It is not known why the second water appears to have affected the soil to such a small extent. The Mackay soil has shown obvious effects from a salt spring which deposited an incrustation indicating an f value of 0·08. The drainage data of the Newlands Field Station are quoted by Schofield, Moon and Knight (1936) and when suitably recalculated show progressive concentration of the water to be accompanied by decreasing f values, *i.e.*, a water with an initial f of 1 has reacted favourably on the soil. Puffeles (1939) showed that a very saline water with an f value of 0·4 drastically reduced the permeability of a Mediterranean soil, the original soil having then become more than half saturated with sodium. Finally, Eaton (1935) has quoted the dual experience with a Californian soil, in one instance rendered sterile in nine years by irrigating at an f value of 0·2 but total solids only 60 grains per gallon, and in the other case producing good crops after 18 years with an f value of 1·9 but with total solids 130 grains per gallon.

The laboratory experiments have therefore been corroborated by field results derived from many parts of the world, and it appears that entry of sodium ions into the exchange complex of a soil may definitely be expected if the f value of the water applied does not exceed 0·5.

Permanence of Degree of Sodium Saturation.

Before proceding to consider the properties of soils saturated to various degrees with sodium ions, it is important to know something of the persistence of the condition under the action of different leaching solutions. Furthermore, Queensland irrigated soils are liable to be subjected from time to time to leaching by heavy rains. Sometimes also there may be a change in the quality of irrigation water applied. The practical questions are obvious. Is it safe to rely on the alternation of rainfall with saline irrigation to counteract the serious effect of the latter on the soil? How can a salt-affected soil be reclaimed? Table 5 sets out some of the data found. It is clear that distilled water (for this purpose the equivalent of rain) has effectively reduced replaceable sodium in all cases. The reclaiming effect of irrigation water No. 12 having an f value of unity is also obvious, regardless of the fact that this water has a total salinity of more than 100 grains per gallon. It is satisfactory to note that each soil type

Table 5.

ILLUSTRATING THE DYNAMIC NATURE OF THE RELATION BETWEEN SOIL AND WATER.

Soil Type.	Sample Used.	Amount of Leaching (acre-ins.).	Replaceable Bases.			
			Ca	Mg (Per Cent.	Na of Total.)	K
EFFECT OF DISTILLED WATER.						
Burdekin Alluvial ..	Cultivated soil ..	Nil	64·1	29·8	4·3	1·8
		43	62·2	33·0	2·9	1·9
Bellenden-Ker Alluvial..	Soil II.	Nil	69·5	16·2	5·3	9·0
		25	69·6	17·3	2·7	10·4
	Soil IIA.	Nil	34·4	41·8	18·4	5·4
		25	44·2	43·6	5·7	6·5
Bundaberg Red Forest..	Soil III.	Nil	70·7	21·9	2·2	5·2
		25	55·5	40·8	1·0	2·7
	Soil IIIA.	Nil	39·0	44·8	14·9	1·2
		25	39·2	52·6	6·8	1·4
EFFECT OF IRRIGATION WATER NO. 12 (f = 1·02).						
Burdekin Alluvial ..	Soil IA.	Nil	54·2	35·2	9·2	1·4
		25	59·7	33·3	5·7	1·3
	Soil IB	Nil	60·6	31·7	5·4	2·2
		25	62·3	29·6	6·4	1·7
Bellenden-Ker Alluvial..	Soil IIA.	Nil	34·4	41·8	18·4	5·4
		25	54·5	29·2	10·9	5·4
	Soil IIB.	Nil	52·0	29·2	12·4	6·4
		25	57·3	28·9	9·9	3·9
Bundaberg Red Forest	Soil IIIA.	Nil	39·0	44·8	14·9	1·2
		25	64·2	27·8	6·3	1·7
	Soil IIIB.	Nil	49·2	39·3	9·1	2·4
		25	62·6	28·4	6·3	2·7
EFFECT OF IRRIGATION WATER NO. 10 (f = 0·27).						
Burdekin Alluvial ..	Soil B_2	Nil	59·3	23·8	15·8	1·1
		25	60·0	17·3	21·4	1·3

gave substantially its own characteristic percentage distribution of exchangeable bases after the final leaching with water No. 12, although the distribution was quite different in both the original soil and in the two intermediate subsamples. All this shows that the reaction of soil and water is, at least in a chemical sense, reversible, and the last water applied (if in sufficient quantity) determines the final state of the soil. In the case of distilled water it is necessary to add that the dispersed condition of a soil partially saturated with sodium ions may reduce the leaching to a negligible rate. In fact Soil A percolated only 10 acre-inches in 10 days under the conditions of the experiment and Soil F proved perfectly impervious to distilled water after having allowed only one acre-inch to pass (see Table 8 for comparable values of other soils). In some extreme cases therefore reclamation by natural leaching under rainfall only becomes an impossibility.

Effect of Replaceable Sodium on Physical Properties of Soil.

Having examined the conditions for the entry of sodium into the soil it remains to find the influence which various amounts of replaceable sodium exert upon the soil. Four different means of detecting physical changes in the soil were tried. The measurements made were the moisture equivalent, the Keen-Raczkowski constants (Keen and Raczkowski, 1921), the rate of percolation of water and the hardness of the soil surface after drying.

Moisture Equivalent.—It was soon found that the moisture equivalent has no value in discriminating between differently treated samples of the same soils. In the first case, because nearly all soils are in good physical condition at the moisture equivalent, no significant differences in the measurements are obtained, and in the second case, soils with a high degree of sodium saturation become so impervious when dispersed that on spinning in the centrifuge excess water is separated at the surface of the soil-cake instead of draining off through the soil.

Keen-Raczkowski Constants.—Coutts' (1930) modified cylindrical box was used, but the soil was put through a 2 mm. sieve instead of through the 100 mesh specified. This avoided unnecessary change of the soil structure. Results of definite significance were obtained. A preliminary testing of the accuracy of the method was made on the virgin Burdekin soil with the test for significance given by Livermore and Neely (1933). Soil fresh from the field was used in six replicates and a further three replications were made on an air-dried sample which had been re-moistened, sieved and dried, with a minimum of working. The results are given in Table 6. The equivalence of the two sets of measurements is satisfactory, for it is most convenient to store soil samples in the air-dry condition.

The whole series has been used to calculate the significant difference between means of any two treatments when duplicate determinations are made and odds are 30:1. It should be noted that the differences given are not for fresh soil and air-dried soil, but for any two treatments regardless of whether or not *careful* remoistening and air-drying have been carried out. Having

Table 6.

ILLUSTRATING THE PRECISION OBTAINABLE IN THE KEEN-RACZKOWSKI TEST.

	Moisture.	Apparent Sp. Gr.	Water Capacity.	Pore Space.	True Sp. Gr.	Volume Expansion.
	Per Cent.		Per Cent. by Wt.	Per Cent. by Volume.		Per Cent.
Fresh Soil	10·05	1·04	62·3	56·9	2·25	Trace
		1·03	63·1	56·8	2·23	Nil
		1·02	62·9	56·6	2·21	Nil
		1·00	61·7	54·3	2·04	Nil
		1·09	63·6	55·3	2·25	4·0
		1·09	62·5	55·0	2·27	2·3
Air Dried Soil	5·12	1·00	60·3	55·9	2·12	2·4
		1·03	58·4	55·8	2·17	2·6
		0·97	63·0	57·6	2·18	1·1
Significant Difference of Constants		±0·09	±3·5	±2·1	±0·11	±3·1

established the precision of the method for the conditions under which it was to be used, it was then possible to examine the treated samples containing various amounts of exchangeable sodium. At the same time it was deemed advisable to study the ill-effect of mechanical handling alone on the soil. To this end the air-dried sample of original virgin soil was subjected to grinding of various intensities in a porcelain mortar. In all cases a "pencil grip" of the pestle and not a "fist grip" was employed. The lightest grinding involved only just enough treatment with the pestle to break lumps so as to pass the 2 mm. sieve. As some of the tests were made with more than two replications the differences necessary for significance are in those cases somewhat less than the maximum values already quoted. It is clear from Table 7 that any large increase in replaceable sodium reduces both water-holding capacity and pore space of the virgin soil by as much as 20 per cent. of the original values. The reduction does not appear to commence until sodium constitutes about 15 per cent. of the total replaceable bases. This does not support the opinion of Ratner (1935), who asserts that much damage has resulted by this stage. The damaging effect of dry-working the soil is illustrated in the second portion of the table. It is possible that this factor is the more important one in the deterioration of Burdekin soils, as a search covering several years has shown only one or two examples of a soil with sodium constituting as much as 20 per cent. of the total replaceable bases. Moreover, the usually very desiccating climatic conditions prevailing for much of the year leaves the soil in an unsuitably dry state for ploughing, and farmers are doubtless loth to irrigate their land for this purpose only. Further, tests by the author have shown that the dry working of Burdekin soil already partially saturated with sodium, greatly increases the hardness of the soil crust which is formed when the soil dries. Table 7 shows also the increase in apparent density which has resulted from grinding the soil, little change being shown in the true specific gravity as determined by the Keen-Raczkowski method.

Table 7.

PHYSICAL CHARACTERISTICS AS AFFECTED BY INCREASED EXCHANGEABLE SODIUM AND BY MISHANDLING THE SOIL.

Soil and Treatment.	Apparent Specific Gravity.	Water Capacity.	Pore Space.	True Specific Gravity.	Volume Expansion.	No. of Replications.	Per Cent. Replac. Sodium.
		Per cent.	Per cent.		Per cent.		
Virgin Soil ..	1·03	62·0	56·1	2·21	1·4	9	4·1
Soil E	1·01	64·1	59·0	2·34	3·3	2	8·3
Soil C	1·04	59·7	56·7	2·28	4·4	2	12·0
Soil D	1·11	54·9	53·4	2·26	6·0	2	16·5
Soil F	1·10	50·1	48·5	2·08	Negative	2	84·9
Soil A	1·08	52·1	53·0	2·22	Negative	2	16·8
Soil B_2	1·04	58·7	55·9	2·24	4·6	2	21·4
Sig. Difference ..	±0·07	±2·7	±1·6	±0·09	±2·4	..	..
Fresh Soil ..	1·04	62·7	55·8	2·21	1·1	6	4·1
Dry Soil Remoistened—							
Minimum handling ..	1·00 ± 0·06	60·6 ± 2·4	56·4 ± 1·5	2·16 ± 0·08	2·0 ± 2·2	3	4·1
Light grinding	1·10 ± 0·07	54·3 ± 2·8	56·2 ± 1·6	2·20 ± 0·09	2·1 ± 2·5	2	4·1
Severe grinding	1·16 ± 0·06	50·7 ± 2·4	50·8 ± 1·5	2·13 ± 0·08	8·7 ± 2·2	3	4·1
Severe grinding	1·18 ± 0·06	48·4 ± 2·2	51·3 ± 1·4	2·24 ± 0·07	5·8 ± 2·0	4	4·1

Percolation Rates.—As a practical test of the soil's actual reaction to the treatment it had received, a very simple percolation test was devised. Cylindrical glass funnels 25 cm. long and 4·5 cm. in diameter, and provided with a glass tap, were fitted with equal-sized filtering pads of cotton wool. Distilled water was added to a mark at 20 cm. above the tap, the air bubbles were removed, and the pads were adjusted to give equal rates of delivery when the cylinders contained no soil. Fifty grams of dry soil were then added to each cylinder and the rate of flow measured, the total head being kept constant to within 2 cm. The filter pads offered a resistance to flow which was negligible compared with that of the soil. A constant-level device would probably have been an improvement, but with sufficient care it was possible to obtain closely reproducible values. The results of these tests are recorded in Table 8 and also shown graphically in Figure 1.

The lower portion of Figure 1 refers to the Burdekin soil and to forms of it containing various amounts of replaceable sodium. The details are to be found in Table 8. The cross-checked curve refers to soil *c*, after it had suffered severe dry working.

The upper portion of Figure 1 refers to the Bellenden Ker and Bundaberg soils, before and after the ingress of exchangeable sodium. The influence of exchangeable sodium in depressing the permeability of the soils is clearly shown by these curves.

Table 8.

Percolation Rates of Soils.

Soil Type.*	Sample Used.	Total Volume of Percolate (ml.).†						Average Rate for 30–60 min. Period. (ml. per min.)		Per Cent. Sodium in Replaceable Bases.
		5 Mins.	10 Mins.	15 Mins.	20 Mins.	30 Mins.	60 Mins.			
Burdekin Alluvial	Virgin soil, air dried	60	115	177	..	250	400	5·0	4·4	4·1
		..	110	142	..	222	336	3·8		
		75	116	155	181	234	362	4·3		
	Virgin soil, air dried, remoistened, and sieved	40	50	55	..	69	..	0·5	0·8	4·1
		49	50	..	..	104	138	1·1		
	Soil E	47	70	95	..	154	268	3·8	3·6	8·3
		62	95	124	..	190	288	3·3		
	Soil C	82	135	180	218	293	464	5·6	5·8	12·0
		84	136	181	222	294	465	5·7		
		60	132	..	215	313	520	6·9		
		73	125	162	..	260	489	5·0		
	Soil C—Lightly ground	45	75	98	..	159	..		3·2	12·0
	Soil C—Severely ground	46	65	83	96	119	168		1·6	12·0
	Soil D	20	23	..	29	33	40	0·2	0·2	16·5
		20	24	25	..	35	40	0·2		
	Soil A	25	40	43	..	51	65		0·5	16·8
	Soil B_2	10	10	10	10	10	10		0·0	21·4
	Soil F	10	10	10	10	10	10		0·0	84·9
Bellenden-Ker Alluvial	Soil II—Cultivated	64	105	135	..	209	345		4·5	5·3
	Soil IIA	58	90	113	..	164	250		2·9	18·4
Bundaberg Red Forest	Soil III—Cultivated	130	190	227	..	314	450		4·5	2·2
	Soil IIIA	97	148	183	..	259	380		4·0	14·9

* For the composition of these soils, *see* Table 3.

† 33 ml.≡1 acre-inch.

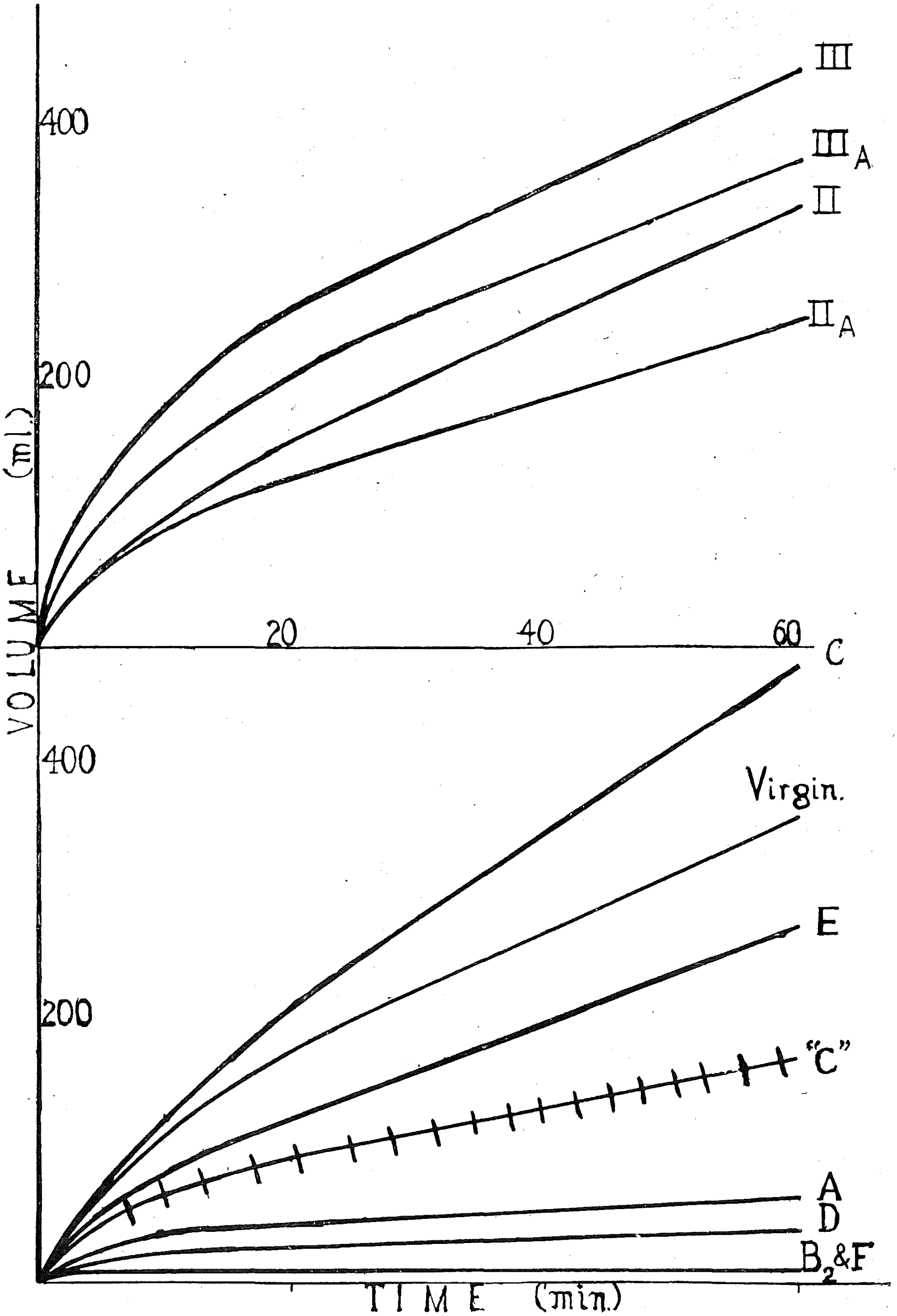

FIG. 1.—Showing the Effect of Exchangeable Sodium on the Percolation Rates of Soils. (See Table 8.)

No claim is made to any high degree of precision for this method, as in one instance a distinct anomaly is obvious (curve 1 lying above curve 4); nevertheless it is clear that as replaceable sodium increases the soil becomes less permeable. There appears to exist a critical value for this sodium content in the vicinity of 15 per cent., since soils with values greater than this are virtually impervious.

Hardness of Soil Crusts.—The most obvious characteristic of any "puddled" soil is the hardness of both the crust formed on the surface and the large clods turned up by ploughing. As a comparative measure of this property readings were made with an instrument designed to indicate rind hardness of sugar-cane, and described by Buzacott (1940). The penetration tests were made on soil treated as follows:—Fifteen grams of soil were placed in a 4 cm. moisture equivalent dish, the soil being allowed to become saturated by standing the dish in water (to the level of the soil); it was then drained and air-dried to remove most of the water, and finally dried at 105° C. Readings were taken as the needle of the penetrometer penetrated the soil cakes. Table 9 shows that the Burdekin alluvial soils showed an increase in hardness as more sodium entered the soil; this effect was not shown by the other two soils. A small effect due to dry working was also shown by all soil types.

Table 9.

SHOWING THE RESULTS OF PENETROMETER TESTS.

Soil.	Hardness (Divisions).
Burdekin alluvial—	
Virgin soil	1
Virgin soil (dry ground)	4
Soil E (8·3% Na)	7
Soil D (16·5% Na)	17
Soil A (16·8% Na)	20
Soil B_2 (21·4% Na)	Beyond range of Instrument.
Soil F (84·9% Na)	
Bellenden-Ker alluvial—	
Normal soil	2
Normal soil (dry ground)	4
Soil IIA (18·4 % Na)	1
Bundaberg red forest soil—	
Normal soil	1
Normal soil (dry ground)	4
Soil IIIA (14·9 % Na)	1

Further tests have been made on these soil types and on one other soil in an attempt to elucidate the effects in general of physical mismanagement of soils. It is hoped to report in a subsequent paper the results of this work.

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