PLANT NUTRITION ON FLY-ASH

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I. INTRODUCTION

The term "Fly-ash" is used to describe an industrial waste material which is produced after the combustion of pulverized coal. Modern power stations produce large quantities of this waste material and the satisfactory disposal of it may present a problem. In some cases it is deposited on low-lying meadows in the form of a low spoil heap or used as a filler for valleys and sand pits. When tipping operations are completed it is anticipated that attempts will be made to cover the surface of the ash with some form of plant cover. The field experiments of Rees and Skelding [12] on the summit of a spoil heap at Hams Hall power station, Warwickshire, indicated that a grass ley could be established if the surface of the ash was first covered with a layer of sewage sludge or sludge/soil mixtures. There were no drought problems although the ash deposit was about forty feet in height. A problem which may arise however concerns the effect of the ash particles on plants roots. This might occur in time when soil and ash became intermixed if the practices of rotational farming were employed on such areas. A knowledge of the plant/ash nutrition interrelationships would appear important in this respect. Such information would be valuable also in cases where a soil or sludge covering was unavailable and a direct seeding of the ash was the only suitable alternative. The natural plant colonization of freshly deposited Hams Hall ash differs markedly from early successional stages which characterize the Black Country waste areas (Rees [13]). The power station ash becomes covered with the

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chenopodiaceous plant *Atriplex hastata* var. *deltoidea* which often forms an almost pure stand (Plate IA) when other weeds and rough grasses are excluded and it was the object of the present investigation to examine ash properties responsible for the exclusion of common weeds and rough grasses which figure prominently in the early plant succession on many other industrial waste materials. It was decided therefore to include *Atriplex* in the experiments using it as a test plant for comparison with various crop plants which were used to examine the plant nutrition potential of the ash.

II. THE COMPOSITION OF THE ASH

1. *Physical properties*

The ash is composed of very fine particles which are easily wind borne and a mechanical analysis of it carried out by hydrometer method and expressed on the Atterberg scale is given in Table I.

TABLE I

Mechanical analysis of the ash

Constituent	Particle size (mm)	Value (per cent)
Coarse sand.	2—0.2	19·78
Fine sand	0·2—0·02	54·00
Silt	0·02—0·002	22·00
Clay	< 0·002	3·10
Soluble matter . . .		1·12

Table I shows that much of the ash is composed of particles of less than 200 microns and replicate measurements indicate that its physical composition is very uniform. The conditions for plant growth might be expected to be somewhat similar to those of a sand culture medium. Its water holding capacity is about 100 per cent and there is no evidence of moisture impedance under field conditions.

2. *Chemical analysis*

A detailed chemical analysis has been obtained from a number of sources. An approximate analysis of the major constituents, kindly supplied by the Central Electricity Authority, is given in Table II. The chief feature of interest woud appear to be the relative high concentrations of oxides of alkaline and alkaline earth metals.

TABLE II

Proximate analysis of the ash			
Constituent	Percentage	Constituent	Percentage
Silica	43·40—51·8	Oxides of potash and sodium	2·60—3·13
Alumina	15·50—29·34	Sulphuric anhydride . . .	1·34—1·88
Ferric oxide	8·25—0·48	Chlorides	0·16—0·30
Ferrous oxide	5·96	Phosphorus pentoxide . .	0·11—0.11
Calcium oxide	6·42—6·82	Combined carbon-di-oxide .	0·06—1·85
Magnesium oxide . . .	1·21—1·60	Combined water	0·13—0·58
Manganous oxide . . .	N.D.—0.42	Carbon	2·12—3·34
Nickel oxide	N.D.—0·01	Free moisture	N.D.—0·27
Titanium oxide	0·60—0·92	Undetermined matter . . .	0·21—0·34

These figures represent the chemical composition of the material as produced in the furnaces. Much of the soluble material will be removed during its prolonged contact with water in the settling ponds in which it may remain for many months before transport to the deposition area. Nevertheless the ash still contains much basic material and the value of the field pH is often greater than 8·5.

The data presented in Tables III, IV and V represent analyses made on a number of randomized samples collected from the ash tip. Table III summarizes the total trace element content as determined by spectrograph. In contrast the values given in Table IV represent what is interpreted by some investigators as the so-called "available" amounts and it will be observed that only about a half listed in Table III can be considered available to plants, and then in only a proportion of their total content in the ash. However, a comparison of the ash and soil available metals (columns 2 and 3 respectively of Table IV) suggest that there is a possibility that Co, Cr, Cu, Fe, Ni, V and Zn may be present in quantities harmful to plants. Evidence will be produced later which suggests that as far as the present observations go these metals are not present in toxic quantities. A number of other conventional "soil nutrient" techniques were also employed to enlarge the general picture of ash nutrient properties, and some of these are summarized in Table V. It would appear that the Morgan's extract may give a truer indication of metal available than, for example, the soil solution, since the amount of aluminium determined by the latter method is much less than amounts present in normal soils. Evidence will be produced later however of aluminium toxicity symptoms exerted by the ash.

The analytical data obtained indicates that the ash may contain

TABLE III

Total trace element content of the ash.
Amounts as parts per million oven dry matter (mean of 4 determinations)

Element	ppm	Element	ppm
Ag	1	Mo	6·50
Be	20	Ni	200·0
Bi	30	Pb	500
Cd	200	Rb	107·5
Co	30	Sc	16·25
Cr	200	Sn	5
Cu	200	Sr	500
Ga	21·25	Ti	3500
Go	17·50	V	300
La	55·00	Y	200
Li	212·50	Zn	750
Mn	3000	Zr	200

TABLE IV

2·5 per cent acetic acid-soluble soil and ash trace elements.
Amounts as parts per million oven dry matter

Element	Ash	Soil	Element	Ash	Soil
Ag	1	1	Ni	60·00	2·70
Co	8·45	1·58	Pb	10·00	10·00
Cr	14·25	1·70	Sn	10·00	10·00
Cu	13·00	3·50	Ti	15·25	10·00
Fe	1774·00	N.D.	V	5·97	1·30
Mo	0·80	0·30	Zn	212·75	168·00

TABLE V

The concentration (ppm) of certain important plant nutrients in the ash as determined by various methods *

Nutrient	Total	In water extract	In CO_2 water extract	In displaced solution	In normal ammonium acetate extract	In 2.5% acetic aicd extract	In Morgan's extract	Method
Nitrogen	490	—	—	—	—	—	—	Macro-Kjeldahl
Phosphate	—	60·0	65·0	—	26.0	625.0	1690·0	Wolf's
Calcium	1770	—	—	—	—	—	—	Distillation
	—	1060·0	—	707.5	—	—	—	Flame photometer
Potassium	—	178·0	—	134·5	—	—	—	,,
Magnesium	—	—	—	231·0	—	—	—	Lindner's
Iron	—	N.D. †	1	N.D.	1	1066	1820	Thiocyanate
Manganese	—	N.D.	32·0	1	9.55	233·0	264·0	Periodate
Aluminium	—	6.6	2.2	1	N.D.	143.5	433·2	Aluminon
Cobalt	—	N.D.	N.D.	N.D.	N.D.	5·0	2.0	Thiocyanate
Nickel	—	N.D.	N.D.	N.D.	N.D.	42.0	16·4	Dimethylglyoxime
Sodium	—	218·0	—	386·0	—	—	—	Flame photometer
Lithium	—	17.45	—	13.5	—	—	—	Flame photometer

* Amounts expressed on oven dry ash basis.
† N.D. = not detected.

a sufficiency of all the essential plant nutrients with the exception of nitrogen. A number of metal ions appear to be present in toxic proportions.

III. EXPERIMENTAL

As this paper is somewhat in the nature of a pioneer investigation in the field of plant nutrition, each successive step in the project depends to a certain extent on the observations of previous experiments. It seemed valid and appropriate therefore to describe techniques employed with the individual experiments in favour of adopting the more conventional method which separates "materials and methods" from "experiments".

1. *Preliminary observations on the nutritional status of plants grown on ash*

Early observations (Rees and Skelding[12]) on the growth of a grass ley mixture on the bare ash containing an N.P.K.-fertilizer showed that the early yields of grass were practically negligible compared with controls. These results suggested that the ash may contain substances which retard ley development and in June 1954 a pilot experiment was conducted to compare the growth of a crop and garden plant, barley and spinach respectively, with that of the successful weed *Atriplex*. Spinach was chosen because of its close taxonomic connection with *Atriplex* while barley is known to be sensitive to a variety of soil disorders.

a) Culture procedure. Seeds of *Atriplex*, collected in the autumn of 1953 from a single plant growing on the ash tip, were sufficient to supply the needs of this investigation. Barley and spinach seeds were obtained locally. One week old seedlings which had been reared in acid washed sand were transplanted to bitumen-painted pots (Hewitt[6]) containing three different media, garden soil with fertilizer, ash with fertilizer and ash alone. The three treatments were employed in quintuplicate. The pots were kept in a greenhouse at 20°C $\pm$ 5°. Barley and spinach plants were harvested for analysis after thirty days but the slower growing *Atriplex* took sixty days to reach maturity.

b) Symptoms and yields. In all treatments *Atriplex* plants showed no visible symptoms of any nutritional disorders (Plate ID). Barley plants growing on both ash treatments remained stunted, lacked tillering; the stems became purple, leaves were narrow and erect with yellow brown lesions on the margins and tips leading to leaf die-back. Later the leaves acquired dark brown spots which coalesced into streaks (Plate IB). These symptoms are very similar to a combination of aluminium toxicity inducing phosphate deficiency together with manganese toxicity (Hewitt[5]). Spinach plants given both ash treatments also developed characteristic symptoms. Plants were dwarfed, leaf margins became scorched and finally dry and brittle. Yield data in the form of height, fresh and dry weights are summarized in Table VI. Whereas both ash treatments are

TABLE VI

Average weights of fresh and dry tops of plants grown on soil and ash

Treatment	*Atriplex*			Spinach			Barley		
	Height cm	Fresh wt., g	Dry wt., g	Height cm	Fresh wt., g	Dry wt., g	Height cm	Fresh wt., g	Dry wt., g
Soil	72·8	5·18	1·04	19·7	10·72	0.69	60·8	5·76	0·56
Ash + N.P.K.	62·8	9·98	1·55	14·2	7·69	0·54	32·6	0·45	0·089
Ash	10·2	0·59	0·04	5·8	2·25	0·14	29·9	0·28	0·057
Sig. Diff. $P = \cdot 05$	6·31	1·67	0·457	4·14	2·53	0·234	6·14	1·37	0·059

detrimental to the growth of both barley and spinach, *Atriplex* flourishes best on the fertilised ash and the values for fresh and dry weight yields are greater on this treatment than on normal soil.

c) Nutrient status of plants

The fresh plant material was washed several times in distilled water before drying to remove aerial contamination (Jacobson[8]). All chemical analysis employed in this and subsequent experiments were made on the oven-dried material by the wet ash method of Wolf[17] with the exception that the digest was diluted with water and not Morgans reagent. The solution obtained by this method was used for the determination of the various elements mentioned. Nitrogen was determined by microkjeldahl.

The alkali and alkaline earth concentrations were measured with the flame photometer.The remaining ions were determined colorimetrically, magnesium by titan yellow (Lindner[9]); phosphorus by amino succinic acid (Wolf[17]); iron by thiocyanate (Treadwell and Hall[15]); manganese by periodate and phosphoric acid to avoid iron interference (Snell and Snell[14] and Nicholas[11]); aluminium by aurine tricarboxylic acid as modified by Chenery[1] and Nicholas[11].

The nutrition status of the three plants is summarized in Table VII *.

TABLE VII

Nutritional status of *Atriplex*, spinach and barley grown on soil and ash

Plant Material	Treatment	N	PO_4	K_2O	CaO	Mg	Fe	Mn	Al
Atriplex leaves	Soil	5·0	1·55	4·47	2·65	0·70	209	68	147
	Ash+N.P.K.	5·02	1·19	4·35	2·42	1·10	285	132	342
	Ash	4·02	1·21	3·51	2·85	1·06	285	130	349
Sig. Diff.	$P = ·05$	0·285	0·201	0·364	0·271	0·086	29·7	26.2	28·8
Spinach leaves	Soil	5·41	2·58	10·40	1·98	0·54	276	27	122
	Ash+N.P.K.	4·61	2·23	8·31	2·08	0·73	386	125	620
	Ash	3·58	2·18	6·72	2·15	0·62	398	111	630
Sig. Diff.	$P = ·05$	0·215	0·283	1·015	0·323	0·043	22.2	6·0	23·1
Barley tops	Soil	5·14	2·57	7·93	1·24	0·26	233	29	32
	Ash+N.P.K.	3·49	0·75	6·48	1·08	0·33	230	46	117
	Ash	3·11	0·80	5·00	1·00	0·33	212	58	105
Sig. Diff.	$P = ·05$	0·233	0·251	0·818	0·186	0·062	14·2	4·9	5·8

Some interesting points emerge from these analyses. *Atriplex* plants on ash alone contain significantly less nitrogen, phosphate and potash than the soil representatives. The addition to the ash medium of these elements raises their plant status somewhat but only nitrogen plant status reaches that of the soil control; the ash plants in both treatments have significantly greater Mg, Fe, Mn and Al status, in fact all ash plants with or without N.P.K. treatments accumulate more of these metals than the soil controls. The addition of nitrogen to the ash does not raise the status of this element in spinach and barley to that of the control. The phosphate levels of barley in both ash treatments is reduced to less than one third of the control. Each plant therefore responds differently to the ash metal content and nitrogen deficiency. *Atriplex* yields and some of its nutrients are lower but it shows no symptoms. Spinach is somewhat similar but it shows aluminium toxicity symptoms.

* In this and in subsequent tables the major elements are expressed as a percentage, the micronutrients as parts per million of the oven-dried material.

Barley is seriously affected through its phosphate content, which is again, in all probability, caused by ash aluminium.

2. *Crop indicator studies*

As the foregoing experiment showed that an excess uptake of manganese and aluminium had occurred in plants used these observations were extended to the use of a number of crop indicator plants which have been shown by Hewitt [4] to be sensitive to excess of these metals.

a) Culture procedure. The indicator plants used included two types of crop plants – *Brassicae*, unaffected by excess aluminium but sensitive to high manganese; a second group included dwarf bean var. masterpiece, runner bean, oats and tomato, since these plants quickly indicate excesses of aluminium. Runner bean indicates toxic quantities of both metals. Flax is stated to be insensitive to excess manganese whereas mustard is a manganese toxicity indicator (Hewitt) [4].

b) Symptoms. On 20th August 1954 seeds of all these plants were sown in replicate in two series of pots containing ash and soil respectively. The ash series was watered with a full culture solution (Hewitt) [6] and symptoms were noted as they occurred.

The brassicae developed marginal cupping and paling of leaf rims, the effect being most marked in cauliflower and least in swede (Plate IF).These symptoms closely resembled those induced by high manganese in sand culture (Hewitt [4]). Manganese toxicity symptoms developed somewhat late in mustard which initially grew more vigorously than the control but the leaves later developed scorched and brittle margins (Plate IC).

Tomato plants were slightly dwarfed (Plate IE); leaves and leaflets curled backwards; leaflets became dull purplish green in colour with brown dry tips recalling phosphate deficiency (Wallace [16]). Oats showed reduced tillering, plants were dwarfed with slightly chlorotic leaves, later showing die-back.

Dwarf beans produced squat plants, leaves became chlorotic and were shed prematurely. Runner beans showed a combination of excess manganese and aluminium symptoms, intervenal paling and necrotic spotting on margins (Mn) later leaf yellowing with premature defoliation (Al), (Plate IIA). Symptoms produced in tomato were very similar to those described by Hewitt [5] for excess

PLATE I. **A**: *Atriplex hastata* var. *deltoidea* forming an almost pure stand on newly tipped ash at Hams Hall. **B**: Barley ash symtoms. **C**: Mustard ash symptoms. **D**: *Atriplex* on ash (left) and soil respectively. **E**: Tomato leaves from soil (right) and ash plants respectively. **F**: Cauliflower ash symptoms.

aluminium. Irregularities in oats also correspond to symptoms induced by aluminium. The symptoms observed in dwarf beans are a combination of both aluminium and manganese toxicities (Hewitt[7]) Flax seedlings wilted, became yellow and ultimately died. These effects are probably due to aluminium. Hewitt[4] found no manganese toxicity symptoms for flax.

c) Plant nutrient status. Leaf samples of six of the original ten plants used were analysed for phosphate, aluminium and manganese. The remaining plants died or became defoliated. The leaf content of the three nutrients is presented in Table VIII in which it

TABLE VIII

Phosphate, aluminium and manganese content of indicator plants grown on soil and ash

Plant	Nutrient status					
	Phosphate		Aluminium		Manganese	
	Soil	Ash	Soil	Ash	Soil	Ash
Cabbage	1·119	1·051	23·2	64·1	18·7	42·7
Cauliflower	1·219	1·018	23·1	44.7	24·6	59·3
Mustard	1·802	1·800	18·0	45·0	30·8	80·0
Sprouts	1·227	1·075	15·5	56·8	15·5	68·6
Swede	1·442	0·983	30·4	52·3	35·7	76·5
Tomato	2·386	1·378	6·1	42·3	42·7	71·3

will be observed that all ash plants except mustard show a depressed phosphate uptake which is reduced to about half the phosphate status of the soil control in the case of tomato. It is noteworthy also that the ash tomato plants accumulate in their leaves some seven times the amount of aluminium absorbed by the soil controls.

3. *Nitrogen levels*

It has been observed in Table V that the ash is very deficient in nitrogen as far as normal crop plant requirements are concerned. The plant *Atriplex*, however, appears to tolerate this deficiency. Experiments were started to examine the behaviour of *Atriplex* under varying conditions of culture nitrogen using barley and spinach for comparative purposes.

a) Culture procedure. Plants were grown in water culture (Hewitt) [6], at five levels of nitrogen, 280 (control), 224, 168, 112 and 56 ppm. In March 1955 one week old seedlings of the three plants mounted on paraffined corks, three per cork, were placed in 1000-ml tall beakers darkened with black paper and connected to a root aerating system.

Mercury vapour lamps supplied auxillary lighting as required. Greenhouse temperature was maintained at 20°C $\pm$ 5°. The experiment ran for six weeks.

b) Symptoms and yields. Except that plants in lower levels of nitrogen were smaller *Atriplex* showed no symptoms of nitrogen deficiency (Plate IID). Spinach and barley both showed marginal scorching of the older leaves at lower levels of nitrogen. Table IX

TABLE IX

Fresh and dry weight yields at reduced nitrogen levels as percentage of control

N in culture, ppm	Tops		Roots	
	Fresh wt.	Dry wt.	Fresh wt.	Dry wt.
Atriplex				
224	107·22	106·22	91·28	107·70
168	78·48	88·56	68·52	75·06
112	50·92	59·58	44·52	44·16
56	41·82	51·84	39·83	21·68
Spinach				
224	78·12	80·00	56·82	63·08
168	21·88	24·12	27·40	31·81
112	15.88	19.77	16·91	21·31
56	8·11	15·56	8·78	13·26
Barley				
224	66·78	78·50	88·78	91·20
168	52·64	62·00	73·91	73·60
112	38·64	50·62	35·51	38·88
56	18·84	41·15	21·63	25·68

summarizes the fresh and dry weight yields of the respective plants. It will be observed that spinach is very sensitive to nitrogen, a reduction of the normal level by one fifth reduces the yield by twenty per cent. *Atriplex,* in contrast, shows an increase in fresh weigth at the same nitrogen level. The total nitrogen content of the three plants is affected in a manner very similar to the fresh weight response.

TABLE X

Leaf total nitrogen of plants grown at reduced nitrogen levels as percentage of the control

N in culture, ppm	*Atriplex*	Spinach	Barley
224	103·20	93·48	87·50
168	94·38	89·00	78·20
112	74·72	62·82	65·42
56	74·72	55·38	46·76

c) Plant nutrient status. Table X summarizes the trend of total nitrogen in the three species as the applied nitrogen concentration is lowered. *Atriplex* is shown to be least affected by nitrogen shortage. Under similar conditions spinach showed a greater fall and its older leaves, in contrast to those of *Atriplex*, showed nitrogen starvation symptoms (Plate IIE). It seemed, therefore, that an analysis of upper and lower leaves of each species for nitrogen at the different levels might furnish information of the behaviour of nitrogen within the respective plants. These analyses were made at the end of the experiment and the results used to obtain Table XI. The

TABLE XI

Percentage ratio of nitrogen content of lower to upper leaves

N applied, ppm		*Atriplex*	Spinach
280		56·5	58·8
224		58·8	56·2
168		67·2	54·8
112		68·0	53·7
56		68·9	39·2
Node number	upper	7 and 8	11 and 12
	lower	1 and 2	5 and 8

nodes were numbered from the base of the stem to the apex in each case. The data shows that at all levels of nitrogen applied the younger leaves have a higher nitrogen content. When the ratio of the lower (older) to upper (younger) leaves is calculated a rather striking result is obtained as shown in Table XI. This ratio increases as nitrogen is decreased in the case of *Atriplex* but the reverse is true of spinach. It seems, therefore, that the export of nitrogen from old to young leaves under nitrogen starvation is much slower in *Atriplex* than spinach.

4. Phosphate absorption

Experiments seemed to indicate that whereas *Atriplex* and spinach maintained a normal phosphate status on the ash, barley suffered phosphate deficiency even if additional soluble phosphate was added in excess. It was assumed that either ash aluminium or iron or both precipitated phosphate as insoluble aluminium or iron phosphates and that phosphate in this form is unacceptable to barley but may be taken in by *Atriplex* and spinach. A simple experiment was set up in April 1955 to ascertain if the phosphate status of plants is materially altered when its supply of phosphate is presented to it in an insoluble form.

a) Culture procedure. On 26th April, 1955 week-old seedlings of *Atriplex*, barley, tomato and two week old plants of cabbage and *Rumex acetosella* were transplanted to two series of water cultures, one containing its phosphate as potassium dihydrogen phosphate while insoluble calcium phosphate was used in a second series. *Rumex acetosella* was included because it is regarded as a plant exclusive to very acid soils where problems of manganese and aluminium toxicities exist, coupled with induced phosphate deficiency.

b) Symptoms. All plants grew normally. There was no evidence of phosphate deficiency.

c) Plant nutrient status. The experiment was terminated after four weeks and the plants were sampled, wet ashed and analysed. The nutrient status of tops of barley and the leaves of the remainder is summarized in Table XII. These data indicate that neither phosphate uptake nor that of other essential nutrients is

TABLE XII

Nutritional status of plants grown with different phosphate sources

Plant	PO_4	K_2O	N	CaO	Mg	Fe	Mn	Al
With KH_2PO_4								
Atriplex	1·93	5·75	5·80	1·32	0·77	290	152	83
Barley	1·58	7·65	5·20	0·81	0·11	217	28	26
Tomato	1·28	4·38	4·60	2·17	0·45	267	66	60
Cabbage	0·98	6·30	4·60	1·71	0·28	157	26	46
Rumex.	1·95	5·85	5·00	0·47	0.32	353	214	44
With $Ca_3(PO_4)_2$								
Atriplex	2·05	5·82	5·85	1·60	0·75	282	160	74
Barley	1·56	7·59	5·20	0·90	0·11	213	29	26
Tomato	1.30	4·05	4·75	2·18	0·44	215	71	28
Cabbage	1·01	6·12	4·80	1·92	0·27	150	26	44
Rumex.	1·80	5·51	5·20	0·53	0.32	306	257	62

affected when an insoluble phosphate source is used. The only exception is a lower aluminium uptake from the calcium phosphate series in the case of tomato. Barley, along with other plants examined, can accept its phosphate from an insoluble salt.

5. *Ash/soil mixtures*

Previous observations have shown that the ash contains a sufficiency of all plant nutrients except nitrogen, in addition it may induce symptoms of aluminium and manganese toxicities in some plants. A series of trials were set up in which the ash was diluted by the addition of varying proportions of soil and a study was made of the effect of these mixtures as compared with either pure ash or soil.

a) Culture technique. The ash was mixed with garden soil in varying proportions by weight to give the following proportions of ash to soil: 12·5, 25, 50 per cent, using pure ash and pure soil as controls. (For mustard, cabbage, brussels sprouts and mangold). A more dilute mixture was prepared for barley at ascending levels of 2 per cent from 0 to 20 per cent ash. On 29th April 1955 the vegetable and barley seeds were sown in these mixtures in large pots. The pots were kept in the greenhouse and given tap water. Seedlings were thinned out to three per pot.

b) Symptoms

1. Mustard plants grew more vigorously on the ash/soil mixtures than either soil or ash alone, but the plants showed typical manganese leaf scorch which increased as ash content became greater. These plants flowered earlier than the soil control (Plate IIF). Cabbage and sprouts (Plate IIB) showed very slight leaf cupping on all mixtures but did not otherwise differ in growth or vigour from the soil controls. Mangold ash/soil plants were larger than soil representatives and were quite normal in appearance (Plate IIC). The sensitive barley showed typical ash symptoms when only 4 per cent ash was present.

2. Yield data and plant nutrient status.

On 24th June, 1955 the experiment ended. Barley tops and third and fourth leaves from other plants were sampled for fresh weight and chemical analysis. Fresh weight data are summarized in Figs. 1 and 2. Most plants show on increasing fresh weight response as the proportion of ash is raised until a maximum yield is reached followed

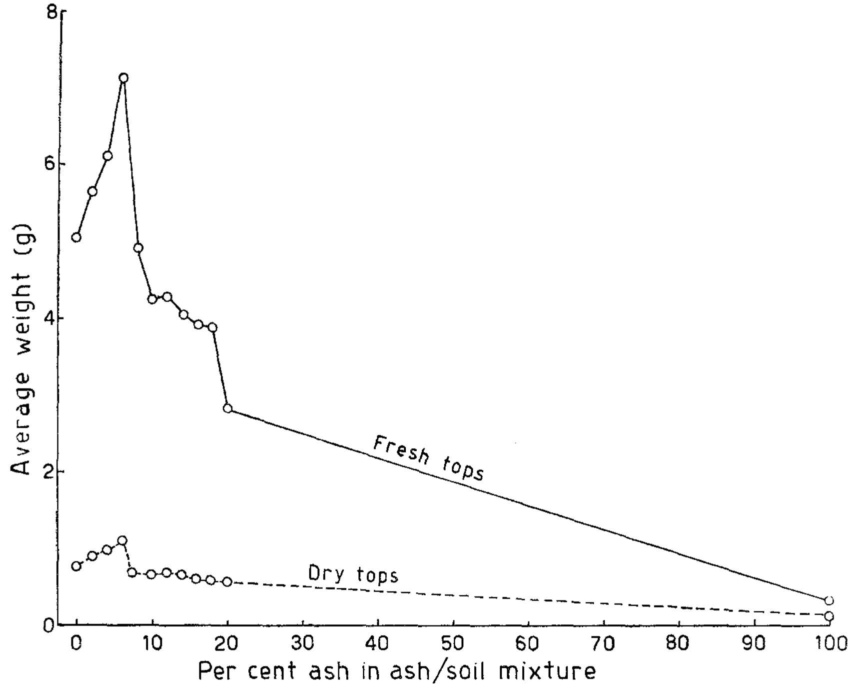

Fig. 1. Barley yields on ash/soil mixtures.

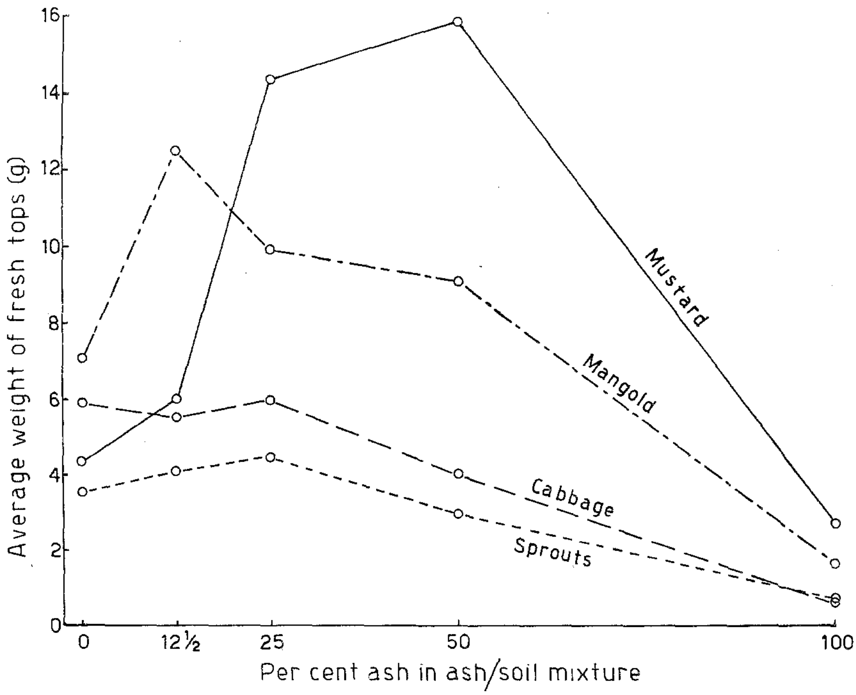

Fig. 2. Plant yields on ash/soil mixtures.

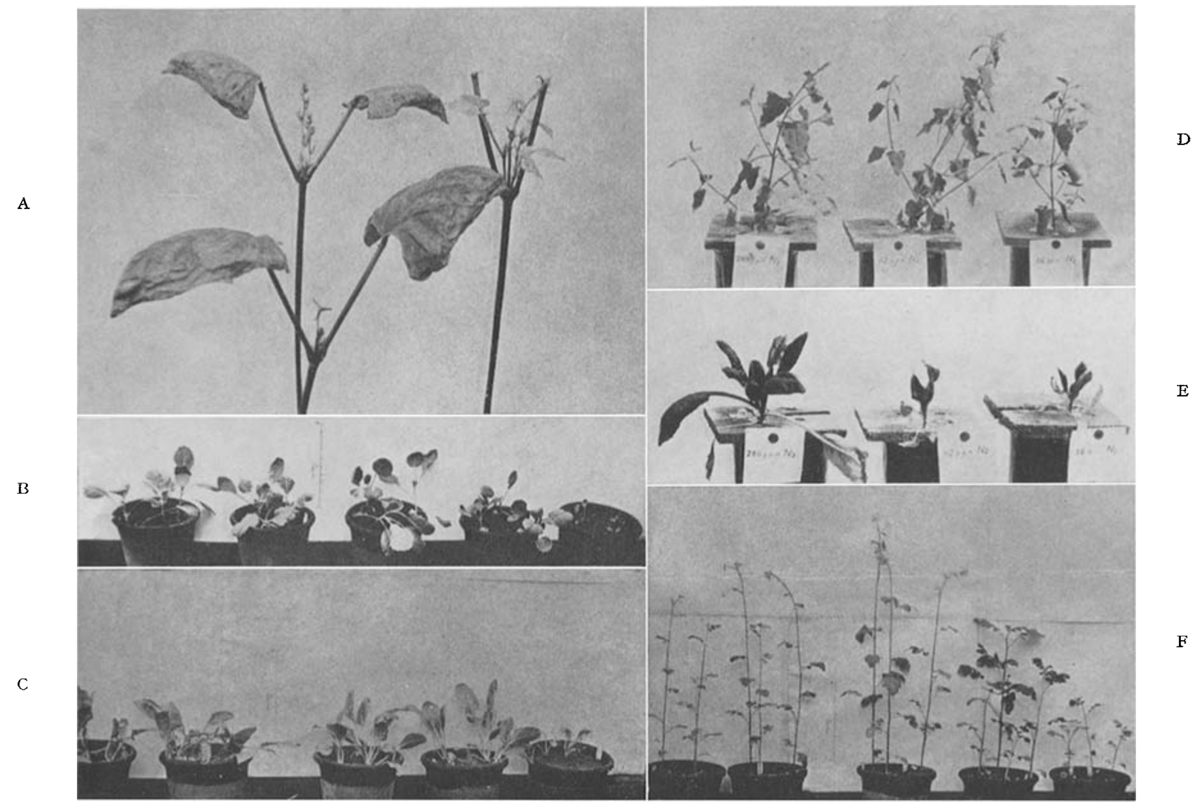

Plate II. **A**: Runner bean ash symptoms. **B**: Cabbage grown on different ash/soil mixtures. Amount of ash used left to right: —0, 12½, 25, and 50 per cent respectively. **C**: Mangold; same mixtures as B. **D**: *Atriplex* grown in water culture at different N-levels; left 280, middle 112, and right 56 ppm respectively. **E**: Spinach grown in water culture at different N-levels; same amounts as D. **F**: Mustard; same mixtures as B.

TABLE XIII

Concentration of plant nutrients in leaves of plants grown on ash/soil mixture

% Ash in ash/soil mixture	Mustard				Sprouts			
	N_2 %	PO_4 %	Mn ppm	Al ppm	N_2 %	PO_4 %	Mn ppm	Al ppm
0	3·90	1·825	30·8	10·0	4·30	1·925	10·0	10·0
12½	3·70	1·825	32·2	27·8	4·00	1·840	20·0	13·4
25	3·60	1·800	38·0	38·9	3·60	1·760	28·0	38·9
50	3.60	1·800	40·2	44·5	3·30	1·440	41·0	40·0
100	3·20	0·775	80.0	50·0	3·00	0.810	68·0	44·5
Sig. Diff. P = ·05	0·204	0·283	6·2	8.3	0·220	0·258	5.5	7.5
% Ash in ash/soil mixture	**Cabbage**				**Mangold**			
	N_2 %	PO_4 %	Mn ppm	Al ppm	N_2 %	PO_4 %	Mn ppm	Al ppm
0	4·30	1·830	16·0	20·0	4·20	2·035	14·2	29·0
12½	4·10	1·810	16·2	20·0	3·72	2·050	20·8	35·6
25	3·60	1·470	18·4	25·6	3·33	1·998	36·0	35·6
50	3·45	1·290	30·0	55·3	3·30	1·870	42·0	40·0
100	3·12	0·585	38·0	62·1	2·95	0·980	70·0	44·5
Sig. Diff. P = ·05	0·182	0·289	5·7	6·3	0·223	0·271	6.6	6.2

by a decline in response. The pure ash yields are the poorest in all cases. The ash/soil ratios producing these maxima vary from as low as 6 per cent in barley to 50 per cent for mustard. Figures given in Table XIII for the nutritional status of some plants in the various mixtures show a fall in nitrogen but an increase in aluminium and manganese as ash increases. Phosphate status is not seriously reduced except in higher ash concentrations when fresh weight is falling.

IV. DISCUSSION

Exploratory enquiries into the plant nutritional potential of an important industrial waste indicate that it contains all the essential nutrients. It is deficient in nitrogen and also contains an abundance of metals which include essential plant micronutrients and a number of other non-essential metals such as nickel. It seems, however, that all these except manganese and aluminium are present in quantities which are harmless to plants, although concentrations of some of them *i.e.* Co, Cr, Fe, Ni, V and Zn do appear somewhat excessive in the acetic acid extract data of Table IV. There is no evidence in our experience of toxic symptoms produced by them. For example the white necrotic streaks produced by toxic Ni on barley leaves are not caused by ash. Perhaps the high Fe status of the ash reduces any potential Ni effect as reported by Crooke *et al.* [2] in oats. Additional support to the hypothesis of the relatively harmless nature of many of the above mentioned metal ions in ash is furnished by data submitted in Table XIV, which summarizes the leaf metal status of cocksfoot plants grown by one of us on ash and soil respectively.

TABLE XIV

Leaf metal status of normal-healthy and ash-Dactylis plants

Metal	ppm oven dry material	
	Normal	Ash
Co	0·64	1·18
Cr	2·0	2·3
Cu	20·2	10·5
Fe	371	650
Ni	13·3	14·8
V	1·4	1·3
Zn	200·6	82

The data presented indicates that perhaps Co, Cr and Fe only might be suspected. However we obtained no evidence of either Co or Cr toxicities in our beet plants grown on ash. The available Fe status of the ash (Table IV) is admittedly quite high, whilst the amount of this metal is greater in the leaves of ash than of soil plants (Tables VII and XIV), barley being an exception in this respect.

The role of this metal in ash may require a separate more detailed investigation. The important conclusions drawn from observations so far clearly point to aluminium and manganese toxicity effects exhibited in different degrees on the various indicator plants employed. Three types of plant responses to excess aluminium may be distinguished: complete tolerance (*Atriplex*), partial tolerance with no phosphate problems (spinach) and great sensitivity to this metal (barley). Aluminium-induced root abnormalities were not evident with ash-barley, due no doubt to high ash calcium (Hewitt [4]).

Atriplex, barley and spinach show increased fresh and dry weight response when N, P and K are added to the ash but in *Atriplex* only does the ash N, P, K response exceed that of the soil. This result suggests that ash contains some property particularly favourable to the growth of *Atriplex* which exerts a very powerful effect when adequate nitrogen is available to this plant.

Manganese toxicity symptoms clearly shown by brassicae grown on ash (Plate IF) confirm that abnormal quantities of manganese are available to plants.

The success of *Atriplex* under conditions of nitrogen shortage seems to be associated with its control of nitrogen drain from old to young leaves. It also suggests a degree of plasticity within this plant as far as nitrogen requirements are concerned since the genus *Atriplex* has often been considered somewhat in the nature of a nitrophilous plant.

The experiments conducted with mixtures of ash and soil indicate that there is a wide range of response by different species to varying proportions of ash to soil. The yield of the sensitive barley is effected by a much lower percentage of ash to soil than either mustard or mangold. Here again there is some indication of a beneficial nutritional effect of ash as far as crop plants are concerned. It is noteworthy also that, although mangold yields are reduced by a high percentage of ash the plants are entirely free from symptoms, in spite of the fact that the plants accumulate large quantities of aluminium and manganese in their leaves (Table XIII). Mangold behaves like the taxonomically related *Atriplex* in this respect.

It would appear probable that many other plants may tolerate the ash aluminium and manganese without much deleterious effect to their growth and yields. It seems that the nutrition problems of the ash may be compared with conditions prevalent within acid soils, podsols and the like which induce both aluminium and manganese toxicity symptoms in crop plants, except that the field pH of the ash is decidedly alkaline. Magistrad [10] has observed toxic aluminium concentrations in alkaline soils, and attributes the effect to a toxic soluble aluminate. It is quite possible that plants may obtain their aluminium in this form from the ash but confirmation of this point is needed.

The absence of the commoner weeds in the early natural succession on the ash may be related to its aluminium content. Gilbert and Pember [3] noted that toxic aluminium in acid soils do inhibit the growth of eleven common grassland weeds. *Atriplex,* however, is immune from this effect.

SUMMARY

1. Chemical analysis of fly ash reveals that it contains an abundance of metals in addition to normal plant requirements. However only manganese and aluminium appear to be available in quantities toxic to plants. The total nitrogen content of the ash is very low.

2. Barley and spinach grown on ash accumulate excessive quantities of aluminium and manganese in their leaves and exhibit symptoms of toxicities of these metals. *Atriplex hastata* var. *deltoidea* however which grows vigorously on the ash has a high aluminium and manganese leaf status but does not show toxicity symptoms.

3. The addition of a fertilizer to the ash increases the dry and fresh weight yields of all three plants but only in the case of *Atriplex* does the ash + N.P.K. yield exceed that of the soil control.

4. The ash aluminium induces phosphate deficiency symptoms in barley but does not affect the phosphate status of spinach and *Atriplex*.

5. A wide range of indicator plants were grown on ash and confirm both by symptoms and leaf analyses aluminium and manganese toxicities.

6. *Atriplex*, barley and spinach grown at reduced nitrogen levels gave lower yields than the normal control but symptoms of nitrogen deficiency which were evident in barley and spinach were not observed in *Atriplex*. The latter plant retains proportionately more nitrogen in its older leaves during nitrogen starvation than either barley or spinach.

7. Crop plants vary greatly in their tolerance to ash and soil mixed in different proportions. Barley is sensitive to low levels of ash showing symptoms and reduced yields whereas others, such as mangold, gave enhanced yields when quite a high proportion of ash was present.

ACKNOWLEDGMENTS

The authors wish to acknowledge their indebtedness to the Central Electricity Authority (Midlands Division) for a grant which defrayed the cost of travelling expenses and certain special apparatus associated with the work, and for permission to use their ash disposal areas.

They also wish to record their grateful thanks to Dr. R. L. Mitchell of the Macaulay Institute for Soil Research who made the spectrographic analyses, and to Dr. E. J. Hewitt of Long Ashton Research Station for his valuable assistance.

Received March 20, 1956.

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