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SEVENTH BOYD ORR MEMORIAL LECTURE

Managing the mineral cycle

By G. W. Cooke, formerly of the *Agricultural Research Council, London**

I greatly appreciate the honour of being invited to give this Seventh Boyd Orr Memorial Lecture. But I appreciate even more the knowledge and understanding of this most remarkable man that I have acquired while preparing for this occasion. This study, which began from duty, quickly became an absorbing pursuit as I read of his career, his scientific work, and his great efforts to improve the lot of hungry people. The qualities that impressed me, seen through the whole of his life, were his determination to pursue a purpose, which, aided by his very great ability and intelligence, led to success in what he undertook, and his sympathy and feeling for the welfare of people. Most impressive to me was the way in which he smoothly transferred from one activity to another. Beginning with training intended to lead to the Church he moved to teaching, then to science and, after qualifying in medicine, he started research in physiology at Glasgow before moving to Aberdeen to found what became the Rowett Research Institute.

After the interruption of the 1914–18 War, in which Lord Boyd Orr served with great distinction and bravery, he established the Institute and developed its programme of work designed to improve animal and human nutrition. In this period Boyd Orr's personal characteristics were vital, partly in securing the financial support of the four Founders, partly in his determination that no financial or bureaucratic obstacles should impede the development of his Institute, and partly in establishing a scientific programme of high quality and great relevance. I think it was Emerson who said that 'an Institution is the lengthened shadow of one man'. This has been true of other founders of our Research Institutes, but never more true than for Boyd Orr and the Rowett Institute, which we owe to his persistence and persuasion. Later his interests developed towards a wider concern for malnutrition of people, caused largely by poverty in this and other countries. This move led to considerable contributions to improved nutrition in war-time Britain, and to a part in 1941 in founding the Nutrition Society of which he was first President. He had a key role (described by David Lubbock, 1963) in the events leading up to the founding of the Food and Agriculture Organization, of which he became the first Director General in 1945.

I never met Lord Boyd Orr. I can best summarize my feelings after reading of his life and work by saying how much I regret that I never had opportunity for

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personal contact with one who clearly benefited society as a whole so much, and influenced and helped those who worked with him.

My interests and experience have been in scientific work on soils, and on crops and their nutrition. The link with part of the work of Boyd Orr I found in an account of one of his Annual Reports to FAO when he wrote 'food production was never fully developed because the aim of western civilization was not to produce the quantity of food necessary to satisfy human needs but rather that which could be sold at a profit'. I fear that scientists concerned with crop production are too often concerned with total quantity of produce, and are influenced by talk of what is, or is not, profitable. Too little attention is paid to 'quality'—which means 'suitability for purpose', particularly when it involves characteristics, such as mineral composition, for which no purchaser pays extra. I have been concerned with work to ensure that plants should not suffer from mineral deficiencies. Boyd Orr was concerned with ensuring that animals that live on plants should also receive sufficient mineral nutrients. These related objectives must be linked more closely; in fact, in future, there should be no discontinuity between those concerned with producing plants and others concerned with using them as food for animals or man.

In this lecture I will take Boyd Orr's book *Minerals in Pastures,* published in 1929, as my starting point. I will describe the intensification of agricultural production since that time with its possible implications for the minerals in crops, and say how we now manage the mineral cycle. Future agricultural developments will raise new problems in mineral nutrition and I will suggest how these may be dealt with. I will also speak about problems involving minerals in developing countries—where Boyd Orr's sympathies were so great.

Minerals for people

Originally I planned to discuss the effects of agricultural intensification on the mineral nutrition of our people. Since we now produce in the UK two-thirds of the temperate region products that we eat (as against a much smaller proportion pre-war) some effects seemed likely. However, the topic is difficult to treat, partly because our diet comes from a variety of sources and, vegetables apart, the components cannot be readily related to the soils and farming systems that produced them. The main problem is that very little has been done towards the comprehensive analysis needed of the effects of changes in fertilizers, lime, farming systems and crop varieties, on mineral concentrations in crops. Agricultural science and food science are not well-linked at their interface, so this intention of mine was frustrated. The only specific recent information on the adequacy of mineral nutrition that I found was for two elements only (calcium and iron); the Ministry of Agriculture, Fisheries and Food's (1980) Survey provided the figures in Table 1. In his classic survey *Food, Health and Income*, Boyd Orr (1936) had showed how malnutrition was a direct result of people having too little to spend on food; this Table shows such effects continue and that individuals in large families may receive too little Fe.

Table 1. *Household food available as percentages of recommended intakes**

	Averages for first and second quarters, 1980	
	National averages	Larger families (2 adults + 3 or more children)
Energy	98	86
Protein	127	110
Calcium	172	139
Iron	102	90

*MAFF (1980).

The best general account of the transfer of elements from soils to plants, to animals and to people, that I met was by Allaway (1975). He concluded that the level of Ca in a diet depended more on the kinds of plants eaten than on Ca levels in soil. However, by liming acid soils, crops can be grown which otherwise would fail on these soils, so 'the use of limestone may offer people and animals a better chance to obtain foods high in Ca'. With copper no direct relationships had been found between available Cu in soil, plant uptake, and Cu status of people; the same was true for Fe, zinc, manganese and magnesium. Phosphorus deficiencies had not been a serious problem in human nutrition; for human food, the main value of P fertilizers was in increasing total food production. Potassium and sulphur fertilizers were also important in producing more food, not in changing its composition. With Zn, however, 'Zn fertilization may be potentially very useful in improving plants as sources of dietary Zn'. Fertilizers generally contributed to the variety and abundance of the food supply and 'there is no evidence from public health statistics that this variety and abundance have been obtained at a sacrifice in the concentration of essential nutrients in the food crops produced'.

Minerals for livestock

Because housed non-ruminants (pigs and poultry) can be fed on scientifically-designed diets based on analysed components, supplementing with minerals where necessary should present no problems. So my comments on the adequacy of minerals in feeds apply mainly to ruminants depending largely or wholly on grass and forage crops. Where problems exist they are most severe where animals rely on the produce of only one soil environment.

The work done in many countries on pasture problems caused by mineral deficiencies was thoroughly reviewed by Boyd Orr (1929) helped by Helen Scherbatoff. Examples of the results they presented, implying a range of problems, are given in Table 2; the samples were arranged in descending orders of feeding value, concentrations of Ca and P diminishing in the poorer pastures. The worst samples were from the Falkland Islands where 40% of lambs born did not survive to be dipped. Much research was done on the effects of mineral content of pastures on the health of stock by the Rowett Research Institute during the 1920s. One set of reports by Elliott *et al.* (1926) and their collaborators describes the wide range

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Table 2. *Average concentrations (g/kg) of minerals in dry matter of different types of pasture**

	Ca	P	Na	K	Cl
Cultivated pasture	7·1	3·2	1·8	26	9·5
Natural grazed pasture	4·6	2·9	2·7	22	6·4
Poor hill pasture	4·0	2·6	3·0	22	6·0
Island of Lewis	2·0	1·0	2·8	6	1·2
Falkland Islands	2·0	2·4	2·3	18	7·0

*Boyd Orr (1929).

of work done in Britain on the composition of pastures, the effects of fertilizers on mineral concentrations in herbage, and effects of supplying mineral supplements. Their descriptions of rachitic diseases caused by deficiencies remind us that 1981 is 'the Year of the Disabled'.

Progress in farming since the 1920s

In the 1920s agriculture was neglected and relatively unproductive and in a paper written in 1920, notable for its clarity and far-sight, Boyd Orr analysed the causes. He pointed out the large gains made by industry from applying the results of scientific research. Agriculture had had little corresponding benefit; apart from improved machinery 'it can hardly be said that any great advance or improvement towards increased production has been made during the past half-century in the practice of agriculture in this country'. He rejected the view that natural factors so limited agriculture that science was of little value to the practical farmer, saying: 'Agriculture is undoubtedly the most scientific of all vocations', it applies 'all the sciences for the production of the prime necessities of life'. He contrasted the British situation with that in the USA and Germany where research was encouraged and the results were applied. Soil was 'the fundamental raw material of farming', but 'we do not even know the principal soil types, nor their distribution —much less their properties and requirements'. Therefore it was impossible to use the £2M worth of imported fertilizers rationally and efficiently; the money wasted in one year was enough 'to establish and endow for all time a research station to investigate this'. But Scotland had to wait 10 more years for the Macaulay Institute for Soil Research to be founded. Similarly £60M had been spent on imported feedingstuffs in 1919, but there was no research station to value the materials.

Boyd Orr concluded the first requisite was a settled Government policy to give security and confidence to farmers so they could adopt a continuous system of farming, and increase production. The second requisite was 'a wide extension of agricultural research and education'. In fact research facilities slowly improved in the 1920s and 1930s and Government gave some financial aid to agriculture in the 1930s. But the settled Government policy had to wait until 1940 when the urgent war-time need for food gave agricultural improvement the highest priority. This policy was confirmed by the 1947 Agriculture Acts and subsequent legislation.

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Under the Agricultural Research Council, formed in 1931, the Agricultural Research Service was greatly expanded in the post-war period (Henderson, 1981).

The result of these two measures, for which Boyd Orr so clearly saw the need, has been the most rapid revolution our agriculture has ever seen. The industry is now completely science-based, and we can take great pride in it for its achievements of producing efficiently twice as much food as in pre-war days from less land with only a third of the labour. As compared with 1930, yields are increased by these factors: wheat $2\frac{3}{4}$; barley $2\frac{1}{3}$; potatoes 2; milk/cow 2; and eggs/hen $1\frac{2}{3}$. Our land carries twice as many cattle and calves and 25% more sheep; we have twice as many pigs and poultry.

The implications for the total mineral cycle are important; our crops require twice the amount of nutrients to be available as in 1930; feed for the larger animal population must contain twice the amount of minerals.

The means of improvement. Apart from a satisfactory economic background, these gains in production have come from applying the results of research done before and after 1940. Breeding has given us crops and livestock of greater genetic capacity. Soil conditions, and crop nutrition, are improved by drainage, lime and fertilizers. Our animals are better fed on a scientific basis. Both plants and animals are protected from diseases and pests by new chemicals and vaccines. Farming systems have been simplified and changed so that the cropping now used is that which suits the environment and economic factors best. Some of these factors have affected the mineral composition of crops.

Plant breeding. Through most of the period when new cultivars have added so much to yield, little notice has been taken of possible differences in mineral composition. Underwood (1979) drew attention to the hazards of seeking higher yields/hectare while ignoring trace element concentrations. He cited a new hybrid ryegrass bred in New Zealand which greatly out-yielded the grasses it replaced, but contained only one-fifth to one-tenth as much iodine—with a consequent increase in goitre. The Welsh Plant Breeding Station programme now includes the breeding of grasses for higher Mg concentrations (Cooper & Breese, 1980).

Fertilizers and lime. We spent £664M on these commodities in 1980—one-seventh of total farm expenditure. Table 3 shows changes in the fertilizers used in

Table 3. *Amounts of fertilizers (thousands of tonnes) used in the UK**

	N	P_2O_5	K_2O
1913	30	183	23
1929	49	201	54
1939	61	173	76
1950	229	468	238
1958	320	392	354
1965	574	487	432
1973	947	482	416
1979	1186	416	416

*Cooke (1971) and FMA (1959–1979).

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the UK. Since 1931 the amount of N used has increased by 26 times, the amount of P by 3 times and the K by 8½ times. As we are mostly concerned with minerals in grassland I give in Table 4 changes in the N, P and K used on grassland in England and Wales, taken from Surveys of Fertiliser Practice (Church, 1981). In the last 30 years the amounts of N used have increased by 10 times on temporary grass and by 15 times on permanent grass. More N could be used on grassland, and particularly on permanent grass; the 5M hectares we have of this crop is an under-used resource, a quarter of it receives no N at all in any one year. The P and K used are probably about sufficient to maintain the grassland systems.

Liming was grossly neglected in pre-war days, only 0·5M tonnes being applied each year in the UK. Surveys showed that very large areas were so acid as to reduce crop growth, even of grass; some soils were so acid that cereals could not be grown at all. The Government responded to this situation in 1937 with the Land Fertility Scheme which gave a subsidy on lime. There was a very good response by farmers (described by Johnston & Whinham, 1980) and Table 5 shows the amounts of lime used. They rose to peaks in 1956 and 1960 and have since diminished. The subsidy stopped in 1976. The amounts now applied are just sufficient to maintain the lime status of our soils, but we must not become complacent.

Effects of fertilizers and lime on the mineral composition of grass. In 1856 Lawes & Gilbert laid down the Park Grass Experiment at Rothamsted to test N, P, K, Mg and Na fertilizers. A test of lime was added later. The herbage has been cut

Table 4. *Average amounts of fertilizers used (kg/ha) on grassland in England and Wales**

	Temporary grass			Permanent grass		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
1943/45	4	11	0	4	11	0
1957	26	34	21	11	20	9
1970	95	44	36	51	28	20
1980	167	35	37	93	21	20

*Church (1981), Cooke (1980).

Table 5. *Total amounts of liming materials* (thousands of tonnes) used in the UK†*

1930	500
1939	1875
1949	5000
1960	7127
1970	4225
1976	4258

*Total weights of materials are stated; in 1976 the amount used was equivalent to 2M tons of CaO.

†From Agricultural Lime Producers' Council (1977).

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for hay twice a year and the experiment still continues. Table 6 gives an outline of effects (on samples taken over 40 years) on the components of the sward and on P and Ca concentrations in herbage (from Warren & Johnston, 1964). Legumes were encouraged by giving P and K fertilizers but N fertilizers eliminated both weeds and legumes. P concentrations in herbage increased when P fertilizer was given but diminished with increasing N fertilizer. Ca concentrations diminished with increasing dressings of N but were maintained better on the limed plots. (The ammonium sulphate used to supply N has made the unlimed soils very acid indeed.)

Table 7 shows effects of the fertilizer treatments on concentrations of Na and Mg in herbage on limed plots. Where K was applied the well-known antagonism was demonstrated, concentrations of both Mg and Na in herbage were depressed; the effect on Na was particularly serious, and Na concentration was not fully restored by a large dressing of this element.

Park Grass does not represent normal grassland management as the experiment has produced hay continuously for 125 years; nevertheless it is useful because effects on mineral composition are very clearly shown under standardized

Table 6. *Concentrations of calcium and phosphorus in hay from Rothamsted's Park Grass Experiment averages for* 1920–1959

Treatments*				Dry matter analyses (g/kg)		
					Ca	
N (kg/ha)	Minerals	Weeds (%)	Legumes (%)	P (Limed plots)	Unlimed plots	Limed plots
0	None	45	14	1·6	9·7	10·3
0	P Na Mg			3·6	8·3	7·8
0	P K Na Mg	26	25	3·0	5·2	7·0
96	P K Na Mg	1	0	2·7	1·5	3·6
144	P K Na Mg			2·7	1·6	2·6

*Mineral treatments supply (kg/ha) 34 P, 224 K, 16 Na, 11 Mg.

Table 7. *Concentrations of sodium and magnesium in hay from the Park Grass Experiment, averages for* 1920–1959*

Treatments (kg/ha)					Analyses of dry matter from limed plots (g/kg)	
N	P	K	Na	Mg	Na	Mg
0	0	0	0	0	3·4	3·3
0	34	0	16	11	4·0	2·6
0	34	224	16	11	0·3	1·8
96	34	0	16	11	5·4	2·6
96	34	224	16	11	0·2	1·3
96	34	224	183	11	2·1	1·3

*From Warren & Johnston (1964).

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conditions. Some plots of this very old grassland are now used by A. E. Johnston for a modern experiment testing N for four silage cuts a year. Yields in the 1970s have averaged 12 t/ha of dry matter (more than leys often produce at Rothamsted) from grass given a total of 375 kg N/ha annually. With this manuring, mineral concentrations have been (in g/kg dry matter) P, 3·5; Ca, 5·6; and Mg, 1·8.

Changes in farming systems

Grassland. This is much improved, though permanent grass does not yet play a full part. The ley-farming doctrine of Sir George Stapledon has been well accepted; a quarter of our grass is in well-managed leys less than 5 years old.

Arable farming. This is greatly changed. Fifty years ago most was still in a Norfolk Four-Course Rotation; often the crops were roots, wheat, clover-ley and barley. The root crops gave an opportunity to kill weeds by cultivation and provided stockfeed; the ley fixed some N. Restrictions on tenancy agreements often prohibited sales of straw—and restricted cropping in ways that conserved plant nutrients. Only grain and animal products were sold. Farmyard manure (FYM) was made and applied to the root crop, sometimes to wheat; it had a vital part in conserving and recirculating all plant nutrients, not just N, P and K. The rotation avoided soil-borne pests and diseases and diminished risks from other crop diseases. The general use of fertilizers removed the constraints that made nutrient conservation essential; developments in herbicides and pesticides during the last 40 years removed the need for rotation. Now every farmer can grow the crops that suit his land and system best; monoculture is quite common, as are cultivation methods that avoid ploughing.

Many farms are now all-arable, no stock are kept and everything that can be sold, is sold. No FYM is made, fertilizers supply the N, P, K, but Mg and trace elements are often ignored and on light soils this can be a hazard for the future. The old farming conserved nutrients, and particularly the K recirculated through FYM. Growing crops for sale imposes a severe drain on K reserves in soil. This is recognized and much K fertilizer is used. In ley-farming systems soil-K reserves must be maintained for the benefit of the arable crops at a higher level than is necessary for the grass phase of the rotation (soil-K status depleted by grass is not immediately restored by fertilizer dressings). The consequence of running at the higher K level is that Mg concentrations in feed crops may be depressed.

I have found no evidence of systematic effects of our modern farming systems on mineral composition of feeds other than those described above—the vital role of FYM and other wastes in recycling nutrients, and the depressing effect of high K levels on Mg and Na concentrations in fodder crops.

Livestock farming. This also is greatly changed. Nearly all pigs and poultry are permanently housed and fed on scientifically-designed diets. Other housed animals, particularly cattle in winter, are no longer kept on the traditional bedding that makes FYM. The excreta from all classes of housed stock are removed as semi-liquid slurries which contain much of the minerals and trace elements in the food eaten. Slurries suit modern handling systems; they are stored in lagoons,

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transported in tanks, and are pumped, not humped! Ten years ago they were regarded as disposal problems, to be spread on the most convenient land, often at wastefully high rates. In fact the excreta from our farm livestock contains three-quarters as much N, as much P, and twice as much K, as is in the fertilizers we use. Considerable increases in fertilizer prices, and stress on the possible damage to the environment from large dressings of slurry, have made farmers aware of the need to spread these materials carefully at correct rates to maintain soil fertility.

The present state of our mineral cycles

I will now review the cycles of important nutrients in British farming systems, so far as the information we have allows. The essential components are: (1) The soil is a bank—with large or small deposits; total amounts of nutrients are measurable, but their availability over long periods is less certain. (2) Inputs of 'new' nutrients are from fertilizers, feeding stuffs, and the atmosphere. (3) Outputs are removed in crops, by leaching and by erosion. (4) Recycled nutrients are in crop and animal wastes.

I will only stress one uncertainty—that is the atmospheric contribution. We have adequate data for deposits in rainfall but terrestrial aerosols contain minerals and trace elements derived from the sea, the land, and occasionally from volcanoes. These are 'washed out' by rain, but they are also deposited directly by a process called 'dry deposition'. At least as much S reaches the land by this route as in rainfall; amounts of other elements are uncertain but may be considerable. Peirson & Cawse (1979) recently stated that the deposit 'of trace elements to the ground is, in some cases, greatly in excess of the amounts removed by crops and could be comparable to the content of the surface soil'. Cawse (1980) gave further results which show the importance of these contributions to this part of the cycle; we need more information to assess our present situation.

Trace elements. In England and Wales trace elements are sprayed on a quarter of the sugar beet, an eighth of the potatoes, and a twentieth of the cereal area; but only 1% of grassland is dressed each year (cobalt applications are commonest). Soil reserves dominate trace element contents of plants, and the cycle. Crops vary in the concentrations they take up; legumes are usually richer in trace elements than other pasture components, or arable crops. In our experience (Williams *et al.* 1960) concentrations in individual crops on one soil are little affected by NPK fertilizer dressings, or by FYM. The cycle in a rotation of five arable crops (wheat, barley, potatoes, kale, clover) at Rothamsted is summarized in Table 8. The fertilizers used supplied only insignificant amounts of trace elements whereas 37·5 t/ha of FYM, given once in the rotation, supplied as much Cu, Mn, and Mo as the crops removed and nearly as much Zn. The soil used contained enough of these nutrients for very many rotations of these crops, provided the total quantities became available.

Few trace element cycles for countries have been published but Kofoed (1980) described the current Cu cycle in Denmark. Some Cu-containing fertilizers are applied; further quantities of Cu are supplied in pig-food and are recirculated in

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manure. The result is that Danish soils are accumulating reserves of Cu at the rate of 330 g/ha per year. The implications for concentrations of Cu in crops have not been studied.

Ca. The lime status of British soils in the 1920s was deplorable but Government aid from 1937 onwards has rectified this. The summary of the present Ca cycle in the UK summarized (with cycles for other elements) in Table 9 indicates that Ca supplies now roughly balance losses by leaching. A recent survey by ADAS of soil pH shows that much grassland is still quite acid and an eighth of the area needs lime now, having a pH value below 5·5.

My reading suggests that Ca concentrations in lowland crops are now sufficient for livestock. Improved lime status diminishes the solubility of most trace elements in soils (except for selenium and Mo where solubility increases with increasing pH). Ca status also affects the uptake of other bases by crops.

P. This cycle (Table 9) is best known and well-documented (Cooke, 1958; Centre for Agricultural Strategy, 1978). When soils are first improved for agriculture the first need is usually for phosphate (and lime on acid soils). P-fertilizers have been used on some British soils for 150 years; the total applied since 1830 is about 27 Mt of P_2O_5, at today's prices this would cost £1000M—or

Table 8. *Total amounts of trace elements (kg/ha) in Rothamsted soil, the amounts removed by crops and supplied by farmyard manure and by fertilizers**

	Total present in soil	Removed by five crops in the rotation†	Amounts supplied by FYM	Amounts supplied by NPK fertilizers
Cu	58	0·3	0·6	0·03
Mn	3100	2·4	3·3	0·02
Mo	2·7	0·01	0·01	0·001
Zn	240	1·8	1·1	0·08

*From Williams *et al.* (1960).
†Receiving FYM + fertilizers.

Table 9. *Estimates* (thousands of tonnes) of components of the mineral cycle in the UK in 1980, annual losses and gains*

Mineral	From† atmosphere	New additions	Taken up by crops	Lost, erosion and leaching	Recirculated in wastes
P	5	245	200	20	210
K	50	>400	1300	50	800
Ca	250	1450	400	1600	200
Mg	150	>100	200	80	100
Na	250	>20	130	160	170
S	1000	?	200	850	100
Cl	700	>350	500	400	150

*The estimates are soundly-based for P, K and Ca; they are more approximate for other elements.
†Allowance is made for dry deposition of sulphur, but not for other elements.

£80/ha! A hundred years ago the P applied was, on average, greater than losses in farming systems and for the last 40 years the amounts have been greater than those taken up by crops. Consequently, our soils have built up considerable reserves of P that are useful to crops and it is now rare to measure an immediate response to fresh P fertilizer in our arable crops or lowland grass. There is no case for increasing the total phosphate applied in Britain but more of the supply should be diverted to upland pastures which need improving.

Because soil phosphate reserves have accumulated we might expect P concentrations in crops to be sufficient for livestock. But in an assessment of the situation Hemingway (1977) wrote 'even under well-managed well-fertilized situations P concentrations in grazed herbage rarely meet the full requirements of productive cattle'. My studies of experimental work confirm this; vigilance is needed, P concentrations in fertilized herbage have varied from 2 to 4 g P/kg dry matter for reasons that cannot yet be explained.

Mg. Table 9 summarizes the components of the cycle for Mg. (As for other elements discussed later, few analyses of wastes have been published and the amounts of Mg, Na, S and Cl recirculated in wastes are uncertain.) In *Minerals in Pastures* Boyd Orr wrote in 1929 'The amount of magnesium present in pastures is probably in all cases more than sufficient for the requirements of the animals grazing'. Unfortunately, this forecast turned out to be untrue; hypomagnesaemia is a serious risk, particularly in spring when Mg concentrations in herbage are less than later in the season. Inputs of Mg are not well known. Dolomitic limestone is applied to a fifth of the area limed in England and Wales; Mg dressings are given to some light arable land and to some pastures. There is risk of low Mg concentrations in all produce from sandy soils where no FYM or slurry is applied. Although Table 9 suggests that the Mg cycle is roughly in balance for the whole country, most authorities consider that the critical concentration essential for cattle, 2 g Mg/kg dry matter, cannot be maintained in herbage throughout the year without supplementary dressings of Mg.

Na. Rain supplies much Na (Table 9), the amounts depending on proximity to the sea; more arrives by dry deposition (Cawse, 1980). Na is readily leached from soil. Although the cycle is in balance, uptake by plants is so affected by K supplies in the soil that no forecast of concentrations in herbage can be made. Licks and supplements in feed are widely used to guard against deficiencies in animals.

Chlorine. Much chlorine reaches the soil in rain (Table 9), particularly near the sea. Large amounts of Cl are applied in K fertilizers. Plants take up much Cl, though the quantities are not essential; the balance is leached from soil, as nitrate is. There were not sufficient analyses of pasture from standardized experiments for me to form an opinion on whether Cl in herbage is always sufficient. In practice nutrition with Cl and Na are closely linked and licks and supplements supply both elements.

S. Plants need about as much S as P. In temperate regions near to industry and urban areas, burning of fossil fuels releases much S which is deposited dry, or in rain (Table 9). Over most of north-west Europe, including Britain, the supply of S is more than sufficient for plants and animals. However, in more remote areas of the northern hemisphere, and much more commonly in the tropics and the southern hemisphere, S is deficient and must be used as fertilizer. Much nearer home, only 3 kg/ha of S falls in rainfall on parts of Ireland and Murphy (1978) has described responses by grass to S-fertilizers in areas of light soils low in organic matter. This situation in Ireland results from a move from ammonium sulphate and single superphosphate to more concentrated fertilizers free of S. It means that we should keep a watching brief on S; changes in fuels and environmental considerations may reduce the emissions of SO_2 and deficiency of S might then occur in western Britain.

K. Plants take up much more K than they do of other minerals (Table 9) and, as I pointed out earlier, large amounts of K must be present in soil to maintain growth of arable crops and pasture legumes. Grasses manage with less K but the minimum concentration needed by animals (5 g K/kg dry matter) is always exceeded. There is no risk of K deficiency in ruminants, but we are concerned about the effects of high K in soil, supplied by fertilizers or manures, on concentrations of other nutrients, notably Mg and Na.

General. For the UK as a whole this discussion suggests that for all of the major mineral elements, the cycle is in balance. While it may be true that all our arable land and productive grassland receive enough minerals, the UK encompasses a wide range of soils and climates; uplands in the north and west would certainly benefit in terms of better pasture growth from more lime and phosphate and the welfare of livestock would also be improved. The survey I made suggests that while ruminants on lowlands generally secure enough Ca in their diets, herbage cannot be relied on to provide enough P, Mg and Na and effective means of supplementation must be considered.

Mineral cycles in developing countries

Boyd Orr (1929) wrote of mineral problems in developing countries, stressing the very low fertility of soils which were even further depleted by exports of agricultural products. At the same time he recognized the great potential of the grazing lands of the tropics, saying that production could well be doubled.

Henzell & 't Mannetje (1980) have described the present position and problems of livestock production in the tropics. Half of the world's pasture land is in developing countries which also have more livestock than all the developed countries (Table 10, from Henzell & 't Mannetje, 1980). But these livestock are very unproductive. The Food and Agriculture Organization (FAO, 1971) showed that developed countries produced several times as much milk and meat as did developing regions with similar numbers of cattle. Many of the soils of developing countries are very poor in plant nutrients and farmers are too poor to improve them. Stock are too many for the pasture available and are underfed. In some areas religious considerations prevent full use of livestock. Mineral deficiencies must be serious where soils are so poor and problems will remain even when more protein and energy can be provided for animals. One important point is that excreta of stock have an essential role in recirculating plant nutrients; in developing countries excreta contain much more N, P and K than fertilizers supply, as the values in Table 11 show. Excreta supply more N and P, and much more K, than are used in the world as a whole. Unfortunately, in some countries, for example India, excreta are dried for fuel instead of being used as manures.

My reasons for stressing the potential for animal production in developing countries are: (1) much land is unsuited to food crops, being easily eroded, but is suitable for pasture; (2) animal protein is needed to improve nutrition, particularly of children; and (3) exports of meat can provide the cash incomes so badly needed by farmers in these countries. I will mention two regions: the humid tropics and India.

Humid tropics. In these regions high temperatures, sunshine and year-round rainfall, give very high potentials for growth of tropical grasses. Possibilities and problems are discussed in a book edited by Sanchez & Tergas (1978). The greatest potential seems to be in tropical Latin America where there are 850M hectares of tropical forest and savannah. The greatest obstacle is the very acid soils. Table 12 compares chemical properties of a typical Oxisol from Columbia with those of a soil under pasture at Rothamsted. The Oxisol has different clay minerals; its small cation exchange capacity is largely saturated with aluminium, it has little exchangeable Ca, Mg and K; Rothamsted soil is well supplied with Ca, Mg and K and contains no soluble Al. That these problems can be overcome has been shown by many years work in Puerto Rico by Vicente-Chandler and his colleagues

Table 10. *Land use and numbers of livestock in developed and developing regions of the world*

	All developed countries	All developing countries
Total land (millions of hectares)	5485	7594
Permanent pasture (millions of hectares)	1278	1780
Cattle (millions)	439	774
Buffaloes (millions)	0·8	130
Sheep (millions)	504	524
Goats (millions)	24	386

Table 11. *Comparisons of the N, P and K in excreta of cattle, sheep and pigs in regions of the world with the amounts applied as fertilizers (millions of tonnes)*

	In animal excreta*			Used as fertilizers in 1979†		
	N	P	K	N	P	K
Far East	19	4·0	26	15·2	2·5	2·2
Africa	9	1·9	15	1·4	0·4	0·3
World	81	17	118	51	13	20

*From Cooke (1977).
†From FAO (1979).

Table 12. *Properties of soils under pasture at Rothamsted and in Columbia*

	Rothamsted (Brown earth)	Columbia (Oxisol)
pH	6·2	4·5
Clay (%)	30	35
Organic carbon (%)	3·0	3·2
Total exchange capacity (mEq/100 g soil)	14·8	4·5
Exchangeable:		
Al	0·0	3·5
Ca	17·0	0·5
Mg	0·7	0·3
K	0·2	0·1

(Vicente-Chandler *et al.* 1974). With lime and fertilizers a realistic target for cut grass is 40 t/ha of dry matter—roughly three times as big as a practical target for UK grassland. The herbage produced had a satisfactory mineral composition; it supported dairy cows receiving salt and steamed bone-flour (but no other supplement) and giving 14 l milk/d; beef cattle were carried at 6·25/ha and gained 1350 kg/ha in a year, no deficiency problems occurred. The main obstacle to development in such regions is lack of capital to purchase inputs. Lime is certain to be an obstacle to development in the humid tropics. FAO (1979) records the amount of lime used in only one developing country—the Ivory Coast. There 4600 tonnes of CaO equivalent was used in 1978 (compared with 1 685 000 tonnes reported for the UK!). Work is being done to develop and use cheaper local sources of lime and rock phosphate. Where N-fertilizer is too expensive, or in drier savannah regions, grass–legume pastures may be the option. Vicente-Chandler (Vincente-Chandler *et al.* 1974) showed that these mixtures yielded about half as much as grasses fertilized with N.

India. This large country presents quite different problems. It is densely populated, having 225M cattle and buffaloes, 110M poultry, and 110M sheep and goats, all competing with 665M people for food from 305M ha of land. Milk production is small, being only equal to 110 g/head of population per d (our production in the UK is about equal to 750 g/head). At present India has only 0·5M 'good' cows yielding about 3000 l/lactation. Sundaresan (1979) stated that over the next 20 years the high-yielding cows will be increased to 20M (they will need to be fed on produce from cropped land). In addition 25M moderate-yielding cows will feed on pastures and crop wastes. The present large population of 50M cows yielding 400 l/lactation will be eliminated. These are formidable objectives. In a critical review of Indian grasslands I read 'The main purpose of the bovines that walk out from the village and back each day is to transform the fibrous grass growth into dung for fuel . . . this cannot go on forever . . .' but change needs 'a complete revolution in outlook and political approach'.

The technical problems involved in change will be enormous. Boyd Orr (1929) reported on the poor quality and bad nutrition of Indian cattle, saying it was difficult to identify specific deficiencies because of the effects of sheer starvation.

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The greatest deficiency was undoubtedly of P, accentuated by exporting bones and not importing fertilizer; it caused low yield, sterility and mortality. India now uses much fertilizer (dominantly N) but it goes to arable land, not to improve the pastures which are unproductive because of poor soil and over-grazing. Other serious deficiencies lie in wait; most common is Zn, from one-quarter to three-quarters of all soil samples tested are deficient in Zn; a third are deficient in Cu; a quarter are deficient in Mn (Randhawa & Bhatia, 1979).

The way ahead

I am convinced that the future will lead towards greater intensification of both crop and animal farming, but with a greater degree of scientific control of the production processes. All trends to greater yield per hectare, or per animal, put a greater strain on the mineral cycle. This is illustrated in Table 13 by stating mineral concentrations in diet needed by high-producing animals and summarized from the latest ARC (1980) recommendations. The same source provided Table 14 which shows that as we require larger growth rates or milk yields, concentrations of some minerals in diet must increase.

Table 13. *Mineral requirements of high-producing animals expressed as dietary concentrations* (*ARC*, 1980)

Type of stock and weight	Daily yield (kg)		Dry matter intake (kg)	Daily requirements (g/kg dry matter)			
	Weight gain	Milk		Ca	P	Mg	Na
Beef cattle, 300 kg	1·5	—	8·8	4·0	2·1	1·0	0·55
Friesian cow, 600 kg	—	30	18·8	3·4	3·1	1·7	1·2
Lamb, 20 kg	0·2	—	0·8	4·5	2·5	1·1	1·1
Ewe, 75 kg	—	3	2·9	3·0	2·9	1·5	1·2

Table 14. *The effects of intensification of animal production on mineral concentrations needed in diet* (*ARC*, 1980)

Type of stock	Daily dry matter intake (kg)	Daily requirements (g/kg dry matter)			
		Ca	P	Mg	Na
100 kg calf: (kg wt gain/d)					
0·0	1·4	1·7	1·1	1·2	0·50
0·5	2·1	5·5	2·9	1·4	0·75
1·0	3·2	6·7	3·4	1·3	0·75
400 kg Jersey cow: (kg milk/d)					
0	3·8	2·5	2·2	1·9	0·7
10	9·0	3·3	3·2	1·4	0·9
20	14·5	3·5	3·5	1·4	0·9

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Sir Kenneth Blaxter (1981) reviewed the potentials for maximum production from crops and animals in his Macaulay Lecture. He quoted 13 t/ha (dry matter) for wheat grain and 29 t/ha for grass (to this I add 90 t/ha of harvested potato tubers). I think a reasonable target for the next few years is to achieve average national yields that are half of these accepted potentials. (A few good farmers, and occasionally experimenters, already come very close to these potential yields of crops, proving they are realistic.) The nutrition of larger crops is readily achieved by fertilizers (with attention to trace elements). The correct nutrition of higher-yielding livestock requires a high concentration of minerals in the diet. This may be achieved by supplementation of hand-fed stock but may not be achieved with any measure of confidence for stock consuming crops or grassland products directly. As I see it the main problem is that we do not have a sufficient knowledge of the factors affecting crop composition and of the factors that may be related to the availability of minerals in different crops to the animal. When concentrations in forage can be forecast correctly, the need for supplementation will be determined precisely and methods of supplying extra minerals can be devised. Some assistance may come from plant breeders who are now working in several countries to produce cultivars with more desirable mineral concentrations. But the greatest problems will be in improving poor soils, particularly in uplands, where soil properties cannot be quickly modified at reasonable cost.

Scientific control of mineral inputs. In planning for scientific control of feeding where minerals are largely or solely derived from grassland or forage crops, analysis of the feed is clearly impossible. The knowledge that a foodstuff mixer can have from his laboratory can only be paralleled by reliable predictions of the effects of soil, weather, farming system, fertilizer and other inputs, on the concentrations of minerals and trace elements in the variety or herbage mixture grown. This information is not available in a co-ordinated and useable form. Work on annual crops has provided some general principles and ideas, but no firm guidance. I think that further progress in investigations on mineral concentrations in crops and grass will only be made from studies on long-term experiments covering a variety of soils and climates, and farming systems, so that general principles can be given a firm numerical basis which will allow predictions for other sites to be made, and possible errors estimated.

Trace elements. The concentrations of trace elements in soil are mainly determined by parent material and weathering process. Solubilities are altered by drainage and lime but total amounts have not been altered by man to the extent that major nutrient concentrations have been changed by fertilizers, lime and cropping. Concentrations in plants are largely determined by soil properties in ways described by West (1979). This topic, trace elements in the soil-plant system, has been a major feature of the work of the Macaulay Institute for Soil Research (for example, Mitchell & Burridge, 1979). Sir Kenneth Blaxter (1981) has welcomed the systematic basis for relationships between soil and trace element concentrations that is being established by the Institute's computerized databank. He emphasized that once we can predict trace element concentrations in feed,

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rather than act after the event, animal suffering will be avoided and resources will be used more efficiently. Scotland is well ahead in this work. England and Wales have not had the same long history of studies of soils in relation to trace elements in plants; Archer (1980) has described the start of an investigation to rectify this. Maps and databases for England and Wales will, no doubt, use as a basis the regional geochemical mapping done by Professor Webb and his colleagues of Imperial College (Webb *et al.* 1978; Webb & Howarth, 1979).

I am more hopeful of having, in a reasonable time, a computerized database serving those who advise farmers for trace elements than I am for the major minerals in crops and forage. For the latter we still have to establish the relationships between soil properties, inputs, weather and mineral concentrations. The large inputs to farming systems have grossly complicated any simple relationship that may have existed in earlier times between soils, minerals and plants. Very great differences between soils do, of course, still dominate uptake of minerals; this has been shown for Mg in three contrasted regions of the USA by Kubota *et al.* (1980). The range of concentrations in herbage of different types reported ranged from 0·2 to 5·1 g Mg/kg dry matter, depending on parent material of soil, on climate and on species of grass.

Conclusions

While the nature and extent of problems of mineral deficiencies in developed and developing countries are at present very different, the kind of scientific work needed to achieve control of deficiencies by advance planning is similar. We are able to predict the need for extra mineral and trace element supplies in crop nutrition. The next step must be to achieve the same measure of control in the nutrition of animals and man. In his 1980 Macaulay Lecture Sir Kenneth Blaxter said it is basically wrong to wait for clinical deficiencies to appear since productivity must be depressed before this stage is reached. It is equally wrong to apply shotgun methods to cover uncertainties. The control of crop nutrition is easier than controlling mineral nutrition of animals since a pool of available nutrients (except N) can be maintained in soil from which there need be little waste. Furthermore, as Middleton (1980) and others have pointed out, for several minerals and trace elements, animals need larger concentrations in their diet than suffice for satisfactory plant growth.

The first need is for a database linking soil properties to plant composition. This is within our reach and can be immediately useful for trace element problems. The second need is to establish, systematically, the relationships between soils, farming systems, inputs, and weather, and crop composition. This will be a big and long job for a multi-disciplinary team of soil and animal workers and statisticians. I am, of course, familiar with the massive ARC (1976) publication (No. 4 Composition of British Feedingstuffs) compiled by Dr. Leitch, Mr. Boyne and Mrs. Garton. This can be the base from which a new study will spring. I realize now the opportunities that have been missed in accumulating data on mineral composition from long-term agronomic experiments, particularly those involving crop rotations, such as the series done by Rothamsted and ADAS to compare ley and arable systems. In such work long-term experiments are essential because the conditions are stable and standardized and full records of inputs are kept from year to year. If a group, such as I have suggested, is set up it would be wise to 'adopt' certain existing experiments and it may wish to propose new ones.

As we might expect Boyd Orr (1929) recognized the need for work of this kind 50 years ago. He said that those involved must be veterinarians, soil and plant growth specialists, plant breeders, and economists: 'The combined effort of workers in all these branches of applied science is needed to solve the great pasture problems'. Boyd Orr never appeared to find barriers to his objectives that he could not push aside. We must do the same and establish ways for the individuals in a multi-disciplinary team to find achievement, satisfaction, and where appropriate, promotion, in a well-led group of interacting specialists.

I must acknowledge the excellent collaboration that has existed between the Macaulay Institute for Soil Research and the Rowett Research Institute, and with other Scottish Research Institutes. I would like to see such work extended, particularly south of the Border. I believe much good working material exists for building the computer-based prediction systems on which we will, in future, rely.

We should not be deterred by the size of the job from starting it. Boyd Orr was not deterred by the size of the world's food problem from tackling it. He set up FAO—which is moving, though slowly, towards the goals he set it. In 1946 he proposed a World Food Board, to have executive powers to stabilize prices, establish emergency reserves and divert surpluses to needy areas. He said such an ambitious proposal might seem premature, but went on 'we are living in a world which is being driven so fast by the advance of science that bold measures are required if we are to solve the tremendous social and economic problems that face all countries'.

I too think that the potential of science must be fully harnessed to improving the quantity and quality of food as well as agricultural prosperity. Boyd Orr (1920) also discussed the application of research—'even when definite results are obtained their practical utility must be tested before they can be demonstrated and absorbed into practice'. This part of the process goes much faster now. Partly this is due to our excellent advisory services; but our well-educated farmers are eager to apply new knowledge and we often find they are waiting for new research to be done to improve their practices—as they are now waiting for more precise guidance on mineral nutrition of livestock. Nowadays a better variety of crop, or a new and more effective pesticide, is adopted immediately. I am sure that sound methods of predicting the quality of food from a knowledge of the conditions under which it is grown will be quickly adopted so that diets can be adjusted in line with the new information.

Finally, may I ask that action on this matter, which is a constraint to efficient animal production, will not be long delayed. In 1920 Boyd Orr wrote 'In original research, indeed, the fruits, though certain, are usually of slow growth and are often reaped by the following generation'. This is one of the very few statements

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made by Lord Boyd Orr that I have seen which I think is not appropriate to our times. I hope that we can move faster in science and its application than was possible in 1920, so that our scientists will have the encouragement of seeing the results of their work make agriculture more efficient in their lifetime.

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