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The uptake of magnesium under exhaustive cropping

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Plants take up magnesium from the soil solution, which is in equilibrium with exchangeable magnesium. Most of the total soil magnesium is not exchangeable, but the non-exchangeable magnesium may be important for replacing the exchangeable magnesium lost by leaching or removed by crops. Modern fertilizers usually contain little magnesium, and using these instead of animal manures, coupled with intensive cash-cropping systems, drains the readily available soil magnesium more than the older farming systems.

Most soil magnesium is in silicate minerals, which in Britain probably include ferromagnesian minerals, micas, micaceous clays, chlorites, and vermiculites. All the 2:1 lattices may have magnesium isomorphously substituted in the octahedral layers of the crystal lattice, and chlorites and vermiculites also hold magnesium in interlayer positions. The clay fraction is likely to contain about two-thirds of the total soil magnesium (Salmon, 1962).

When aluminium is released from acid clays, lattice magnesium will also be released, and this explains the increased magnesium saturation of acid soils that are much leached (Barshad, 1960). The decomposition of clays varies with acidity and temperature (Osthaus, 1956; Coleman & Craig, 1961), and the release of magnesium depends on the nature, composition, and particle size of the minerals (Ståhlberg, 1960).

Metzger (1929) reported increases in exchangeable magnesium on incubating moist soil. Magnesium has also been released to soybeans from olivine mixed with acid beidellite, and from the beidellite lattice itself (Longstaff & Graham, 1951), but Michael & Schilling (1957) found that, in exhaustive cropping, flax used only exchangeable magnesium, and in a long-term trial with potatoes non-exchangeable magnesium was released more slowly than potassium.

Much non-exchangeable potassium can be released over a cropping period; the releases have been related to the potassium content of the fine ($< 0{\cdot}1\mu$) clay fraction (Arnold & Close, 1961). The mode of release of interlayer potassium is not fully understood, but interlayer magnesium may be released from chlorites and vermiculites; Ståhlberg (1960) considered these were the main sources of magnesium released from Swedish soils, rather than illite, which released magnesium more slowly. The pattern of magnesium release may differ considerably between soils containing different amounts of these minerals.

We investigated the possibility that non-exchangeable magnesium becomes available during extended cropping, by attempting to exhaust a selection of English and Welsh soils in the glasshouse. Perennial rye-grass was the main test crop, but some comparisons were made with clover, which usually contains a larger percentage magnesium than grass grown in mixed pastures.

MATERIALS AND METHODS

The soils were mainly from uncultivated sites, to avoid possible residues from previous manuring. They were derived from a range of parent materials, which included at least 24 soil series, and had a wide range of chemical and physical properties. Salmon (1962) described the soils and gave analytical data. These are also in an Appendix to this paper, which will be supplied on request. Briefly, the clay contents ranged from 2 to 46 %, pH from 3·3 to 7·6, total magnesium from 0·04 to 5·20 %, and exchangeable magnesium from 0·6 to 31·6 mg./100 g.

Magnesium was determined spectrochemically (Scott & Ure, 1958). Total magnesium in the soils was measured after decomposing them with HF–$HClO_4$, and taking up the residues in hot 5N-HCl. Exchangeable magnesium was extracted by shaking 2 g. of soil with 50 ml. of neutral N ammonium acetate for 1 hr., and filtering. This method extracts only slightly less magnesium than leaching with 100 ml. of solution, and it diminishes variations from partial solution of carbonates or the possible slow exchange of interlayer magnesium in some soils. pH was determined in 1:2 suspensions of soil in 0·01 M-$CaCl_2$ solution. Mechanical analyses were made with a Bouyoucos hydrometer, after destroying organic matter with hydrogen peroxide,

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and dispersing with dilute Calgon solution—25 ml. of 5 % Calgon (pH 9) to 50 g. of soil, shaken overnight.

Soils 1–41 were cropped with perennial rye-grass and soils 17, 18, 41–44 were also cropped separately with both grass and white clover. 350 or 400 g. of soil per pot was used in the first experiment, and 150 or 180 g. in the second. Triplicate glass pots of each soil were set up in randomized blocks, but one replicate was discarded after checking the uniformity between the other two at the first harvest. Each of the larger pots received a basal dressing of 45 mg. N and 50 mg. P as $(NH_4)_2HPO_4$ followed by standard weekly additions of NH_4, Ca and K nitrates in amounts intended to balance crop uptake; 25 mg. N, 5 mg. Ca, and 8 mg. K were applied each week except in winter, when half as much was given because growth was less. The smaller pots received only 40 % of the nutrients given to the larger pots. The demineralized water applied contained traces of sodium but magnesium was undetectable after concentrating twenty times.

The larger pots were sown with 0·25 g. of perennial rye-grass seed (S. 23), and cropped continuously for 11 months (April–March) unless growth had ceased earlier. The smaller pots were sown with 0·1 g. of grass seed, or with 7 pre-germinated seeds of Dutch white clover, and were cropped for up to 8 months (August–March). Supplementary lighting was given from November to March by high pressure mercury vapour lamps. The crops were harvested at monthly intervals except in late winter, when the last two cuts were taken at 6-week intervals.

After drying overnight at 100°, the harvested material was dry-ashed at 400–450° and then HCl-digested. Samples from duplicate pots were usually bulked before ashing, but those from harvests 1, 4, and 6 were analysed separately to check the standard errors, which were less than ± 0·015 % Mg.

When the pots were taken down some of the soils were sampled while still moist to test the effect of drying on the extraction of exchangeable magnesium. All were then dried, crushed and sieved, separated from roots and stubble, and the fine roots were collected by vacuum suction on a muslin screen. The residual exchangeable magnesium was determined in the separated soils.

The roots and stubble were assumed to contain the same percentage Mg as the final crop harvest. The sum of magnesium removed by harvested crop, and stubble and roots, plus the residual exchangeable magnesium was called 'exhaustion' magnesium.

RESULTS AND DISCUSSION

Magnesium contents of roots and stubble

Preliminary analyses showed that determining percentage Mg in roots and stubble would be misleading; Table 1 shows the differences found between various parts of grass plants after the final harvest. These differences seemed unlikely to reflect real differences between the plant materials. The soil was separated in a dry way because it was required for analysis, but the fine soil particles adhering to the roots were not all removed. The magnesium contents of whole soils do not differ much from those of plant materials, but the undefined soil fractions adhering to the roots might have contained much more, so exaggerating the magnesium content of a contaminated root sample. Contamination by soil was tested by ashing samples of grass, stubble, and roots to constant weight at 450°, and comparing the weights of ash as a percentage of oven-dry material; Table 2 shows considerable contamination of roots with soil. Stubble cut above soil level was probably not contaminated in the same way, but much moss grew in some pots; this was not separated from the stubble, and might have caused discrepancies. For this reason the magnesium concentrations in roots and stubbles were assumed to be the same as in the corresponding final crop harvests. This has led to some uncertainty in the calculated total magnesium uptakes, especially when the roots and stubble formed a considerable part of the total plant material produced.

Residual exchangeable magnesium

Some exhausted soils, which were subsampled while still moist after cropping, were extracted with N ammonium acetate both before and after air drying. Extractable magnesium increased in some soils after drying, and in some continued to increase after a series of wetting and drying cycles at room temperature. Table 3 illustrates these effects on six soils.

It was difficult to sample moist, root-filled soil and the moist subsamples were not considered representative of the whole soil mass, so the residual exchangeable magnesium contents used in computing 'exhaustion' magnesium values were determined after drying and separating from roots.

Table 1. Mg *in grass at final harvest*

(% Mg in oven-dry material.)

Soil	Grass	Stubble	Roots
14	0·127	0·237	0·148
17	0·308	1·050	0·586
19	0·122	0·203	0·780

Table 2. *Ash in grass at final harvest*

(Ash, % of oven-dry material.)

Soil	Grass	Stubble	Roots
14	9·6	13·8	26·4
17	9·8	13·3	25·8
19	8·5	12·8	19·5

Although these residual magnesium figures may be larger than in the undried soils, the initial exchangeable magnesium had also been determined on air-dry soils, and the two measurements were comparable.

Uptake of magnesium by grass

In the early harvests the magnesium concentrations in grass and uptakes of magnesium were poorly correlated with the exchangeable magnesium contents of the soils, but as cropping continued the total uptakes approximated more closely to the exchangeable magnesium. The second harvest usually removed more magnesium than the first, possibly because most of the root growth occurred during the earlier period. Thereafter the monthly uptake of magnesium from most soils decreased with successive harvests, suggesting that the available magnesium was being progressively depleted and not replenished. This is illustrated in Fig. 1 for several soils of different magnesium-supplying power. Later uptakes may have been smaller than earlier ones because yields were smaller in winter, but these yields were compensated to some extent by larger concentrations of magnesium; yields were reasonably constant through the summer and autumn.

If non-exchangeable magnesium was released during cropping, the rate of uptake might be expected to decrease at first but then to approach a constant rate close to the release rate. The shapes of the curves in Fig. 1, relating uptake to time of cropping, indicate that any release of magnesium occurs rather slowly.

Uptakes of magnesium from most soils had become very small by the end of cropping, but with some soils this was because yields were also small, because of factors other than magnesium supply, for the magnesium concentrations were relatively large. These soils may have been deficient in another nutrient or may have had toxic quantities of other substances. Harvested crops removed at least 100 lb./acre of magnesium from more than half the soils. Several soils supplied over 200 lb./acre (assuming 1 acre equivalent to 2 million lb. of soil).

Uptakes may have been affected by factors other than the amounts of available magnesium in the soils, and possible releases are indicated better by taking account of the residual exchangeable magnesium.

'Exhaustion' magnesium and the initially exchangeable magnesium

The 'exhaustion' magnesium values were the sums of the magnesium removed by harvested crops, and by stubble and roots, plus the exchangeable magnesium extracted from the dried soils separated after cropping. The contributions by stubbles and roots are approximate, and those of the residual exchangeable magnesium are probably slightly larger than in the moist soils immediately after cropping.

All the 'exhaustion' magnesium values were more than the initially exchangeable magnesium, and overestimation of the residual exchangeable magnesium was not enough to account for the differences. Some non-exchangeable magnesium might have been released during cropping, but the 'exhaustion' and initial exchangeable values were closely correlated ($r = 0{\cdot}990$). The 'exhaustion' magnesium was on average 1·2 times greater than the exchangeable magnesium. The points which lay appreciably above the regression line were for soils for which the assumed magnesium contents of roots and stubble made substantial contributions to the 'exhaustion' magnesium figures; consequently they were less reliable than other points.

There are two alternative conclusions: either the presumed magnesium release was closely related to the initial exchangeable magnesium, or magnesium release was negligible and the exchangeable

Table 3. *Effect of wetting and drying on exchangeable magnesium of exhausted soils*

(Exchangeable Mg, mg./100 g. soil.)

Soil	Exhausted soil: Moist	Dried once	Dried 5 times	Uncropped soil, initial
3	4·35	4·58	5·24	8·88
11	1·88	2·81	3·78	5·35
14	1·05	1·07	1·08	5·23
20	0·79	1·28	1·97	9·12
24	0·64	0·74	1·04	4·26
25	1·00	1·38	2·41	6·57

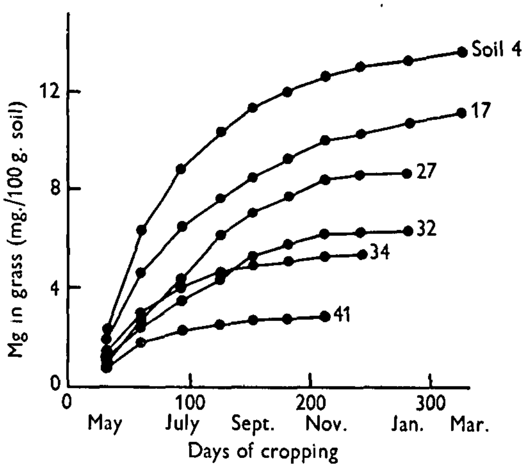

Fig. 1. Uptake of Mg by perennial rye-grass.

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magnesium was only proportional to, but not equal to, the available magnesium. It seems improbable in such a range of soils that the magnesium release should be so closely related to exchangeable magnesium, but, in uncropped soils, exchangeable magnesium may have been determined by the intrinsic rate of magnesium release. However, there is no reason why the quantities of a cation extracted by a strong salt solution should be the same as those available to plants. Kelley (1948) comments that exchangeable magnesium is often an indefinite measurement; it is possible, therefore, that a modified technique could have been developed to extract amounts of magnesium similar to the 'exhaustion' magnesium figures. Because of uncertainties implicit in calculating the 'exhaustion' magnesium, it can only be concluded that releases of magnesium are small in comparison with the amounts 'available' from the outset, and that the 'available' magnesium was largely in the exchangeable (+water-soluble) forms.

Uptake of magnesium by rye-grass and white clover

Clover failed to grow on soil 44, and on the others grew more slowly than grass; the first clover harvest was taken at the same time as the second grass harvest. As with grass, magnesium uptakes by clover declined progressively with continued cropping; uptakes by the two crops differed in the early stages, but later they were more similar.

There was no clear difference between total magnesium uptakes by grass and clover, nor in the 'exhaustion' magnesium figures. 'Exhaustion' magnesium is plotted against initial exchangeable magnesium in the same figure as for the main grass experiment (Fig. 2); these results were not used in calculating the correlation coefficient. Grass and clover seem to have drawn on the same sources of available magnesium, and where the crops grow together in the field total uptakes of magnesium may not be greatly affected by different proportions of the two species.

Magnesium release in nature

Release of mineral magnesium by weathering may suffice to maintain adequate levels of available magnesium in field soils. The amounts in the soils studied probably resulted from a balance between release by weathering and loss by leaching; the balance will be upset by cropping, but most field crops take up small amounts of magnesium and uptakes become less as the supply diminishes. Even if magnesium release was negligible in the intensive cropping used in this work, where most soils supplied over 100 lb./acre of magnesium during a few months cropping, it may still be important in the field.

The amounts of magnesium extractable from exhausted soils were increased by air-drying. The reason for this is not known, but the increases from a series of wetting and drying cycles sometimes exceeded the amounts originally extractable from the moist soils, and this suggests how field soils may be prevented from becoming exhausted of available magnesium.

In the Broadbalk winter-wheat experiment at Rothamsted the response to added magnesium has not increased after nearly 100 years of cropping (Russell & Watson, 1940); on light Scottish soils no response has been obtained to magnesian limestone during 14 years of cropping (Reith, 1962). These results show that field soils may be difficult to exhaust, provided they initially contain much magnesium. Where the available magnesium is already little, however, rapid depletion by crops might not be made good by release from non-available forms.

SUMMARY

1. A range of soils were cropped exhaustively by perennial rye-grass for up to eleven months in the glasshouse; some were also cropped with Dutch white clover.

2. At least 100 lb./acre of magnesium was taken up from most soils, and some soils supplied more than 200 lb./acre. The amounts of magnesium taken up decreased with successive harvests, suggesting that the available magnesium was progressively depleted. Although the 'exhaustion' magnesium (Mg taken up by crops + residual exchangeable magnesium) was greater than the initial exchangeable magnesium, these two measurements were

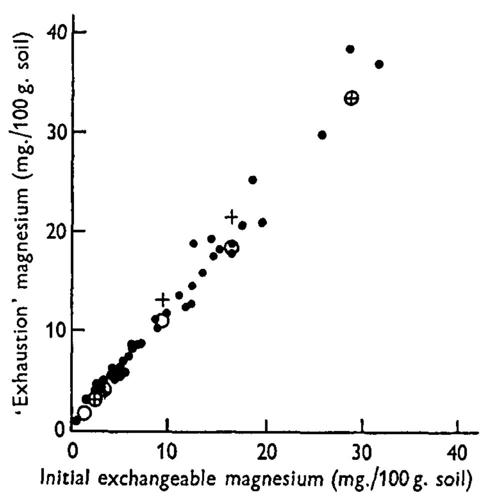

Fig. 2. 'Exhaustion' magnesium and the initially exchangeable magnesium. ●, Perennial rye-grass (main expt.), ○, perennial rye-grass (subsidiary expt.); +, white clover (subsidiary expt.)

closely correlated ($r = 0{\cdot}99$). If non-exchangeable magnesium was released during cropping, the releases were proportional to the initial exchangeable magnesium contents. However, the exchangeable magnesium measurements may have extracted only a proportion of the magnesium available naturally.

3. Any releases of magnesium were small compared with the amounts available from the outset, and the crops obtained magnesium mainly from the exchangeable form. Rye-grass and white clover gave similar results.

4. The exchangeable magnesium in some exhausted soils was increased by wetting and drying. This effect may occur in the field, where the magnesium lost in cropping could be replenished by only small releases of non-exchangeable magnesium.

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REFERENCES

Arnold, P. W. & Close, B. M. (1961). *J. Agric. Sci.* **57**, 295.

Barshad, I. (1960). *Trans. 7th. Int. Congr. Soil Sci. (Madison)*, **2**, 246.

Coleman, N. T. & Craig, D. (1961). *Soil Sci.* **91**, 14.

Kelley, W. P. (1948). *Cation Exchange in Soils*, p. 79. New York: Reinhold.

Longstaff, W. H. & Graham, E. R. (1951). *Soil Sci.* **71**, 167.

Metzger, W. H. (1929). *Soil Sci.* **27**, 305.

Michael, G. & Schilling, G. (1957). *Z. PflErnähr. Düng.* **79**. 31.

Osthaus, B. (1956). Clays and clay minerals. *Bull. Nat. Res. Coun., Wash.*, **456**, 301.

Reith, J. W. S. (1962). *Emp. J. Exp. Agric.* **30**, 27.

Russell, E. J. & Watson, D. J. (1940). *Tech. Commun. Bur. Soil Sci., Harpenden*, no. 40.

Salmon, R. C. (1962). Ph.D. thesis, London University.

Scott, R. O. & Ure, A. M. (1958). *Analyst*, **83**, 561.

Ståhlberg, S. (1960). *Acta agric. Scand.* **10**, 205.