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NITROGEN-MAGNESIUM RELATIONSHIPS IN CROP PLANTS

by E. G. MULDER *

Agricultural Experiment Station and Institute for Soil Research T.N.O., Groningen, the Netherlands

INTRODUCTION

The uptake, translocation and perhaps the assimilation of cations and anions by plants depend not only on the concentrations and the availability of these ions in the nutrient medium but also on the presence of other cations and anions. The absorption of calcium, for instance, may be depressed by excessive amounts of potassium or magnesium, but favoured by nitrate. Similarly the uptake of phosphate may be depressed by nitrate but increased by ammonium ions. Further examples of interactions between inorganic nutrients are: nitrogen—copper [39 41], sulphate—molybdenum [42 62], manganese—molybdenum [42], and phosphate—molybdenum [42 62]. The former three represent interactions of the antagonistic type, the latter of the synergistic type.

The mechanism of these interactions is not always clear; in many cases it depends apparently on an ion competition on colloidal surfaces, either at the surface of the cell or within the cytoplasm. The competition between ions for binding sites on the hypothetical, metabolically generated, carriers is presumably also of great importance [12 46 47]. The favourable effect of phosphate on molybdenum uptake and translocation within the plant and of calcium on potassium absorption [46 47] are of a different character. So far their functioning is not explained.

If plants are grown under natural conditions such interactions may also be found to have their origin in the soil.

Of the elements essential to plant growth, magnesium is particularly subject to a number of interactions with other nutrient elements. The existence of a calcium—magnesium antagonism was demonstrated as early as 1892 by Loew [29].

Of much greater practical importance is the hydrogen—magnesium relationship which plays an important role in plant nutrition on light, sandy soils in

* Agronomist of the "Landbouwkundig Bureau der Nederlandse Stikstofmeststoffen-Industrie".

Western Europe [11 13 14 15 19 23 25 28 40 48 54 55 60 61]. A decrease of soil pH due to a prolonged application of ammonium sulphate was found to bring about magnesium deficiency of the crops. The opinions of various authors as to the cause of this phenomenon differ considerably, however. Gehring [14 15] and a number of other German authors [55 60] suppose that the reduced uptake of magnesium by plants growing in acid soils is due to a reduced availability of soil magnesium, owing to a fixation of magnesium by the soil constituents under acid conditions. No evidence in favour of this assumption is, however, presented by these authors. Although a fixation of magnesium in the soil may occur [26 32 40], there is no indication that this happens in light soils at low pH values. It rather takes place in alkaline soils and at a relatively high magnesium level. Smit and Mulder [61], who have made an extensive study of the magnesium nutrition of cereal plants on acid soils, were unable to demonstrate a fixation of magnesium by an acid sandy soil when the latter was incubated for 2½ months at 25°C in a moist condition. The low content of plant-available magnesium in acid soils was attributed by these authors to a leaching of this nutrient element by the winter rains. That considerable amounts of magnesium may be lost from acid soils by leaching was also shown by Schmitt [56].

Van Itallie [20] ascribed the frequent occurrence of magnesium deficiency on acid soils to the interference of H-ions with the uptake of magnesium ions. In addition, an excess of H- and NH_4-ions and of inorganic anions within the plant tissue was assumed by this author to increase the magnesium requirement of the plant. The beneficial effect of nitrate was attributed partly to an increased uptake of magnesium from the soil and partly to its neutralizing effect. Ferrari and Sluijsmans [13] who studied the magnesium nutrition of oats growing under field-experiment conditions, found, that when equal contents of available magnesium were present in the soil, more pronounced symptoms of magnesium deficiency occurred at a low than at a high pH.

The influence of the pH of the nutrient medium and of the kind of nitrogen compound applied, on the uptake of inorganic nutrients has been studied by a number of workers. Arnon [2] grew barley plants in culture solutions with nitrate and ammonium nitrogen, respectively, at different pH values. Nitrate plants were found to have a lower phosphorus content but a higher calcium, magnesium and potassium content than ammonium plants. There were practically no differences in uptake of these elements by plants grown at pH 5, 6 or 6.7. In a subsequent paper Arnon *et al.* [3] studied the effect of the pH of the culture solution on the uptake of inorganic nutrients by tomato, lettuce and Bermuda grass over a relatively short period of time (96 h). In tomato and lettuce, uptake of K, Mg, P and particularly that of Ca was lower at pH 4 than at higher pH values. Nitrate uptake by these plants was not affected by the pH in the range from 4 to 9. In Bermuda grass, uptake of calcium only was depressed by a high hydrogen-ion concentration. Wadleigh and Shive [64] found that the effect of the kind of N supplied, on uptake of cations by maize plants was of much greater importance than that of the pH of the culture solution. The total base content of the ammonium plants was approximately 80% of that of nitrate plants; with both N-compounds it was constant between pH values from4 to 8. Uptake of calcium was more depressed by the presence of NH_4-ions than that of magnesium and potassium. Michael[33] found that the uptake of magnesium from culture solutions by young maize and rye plants was considerably lower at pH 4.0 than at pH 6.0 or 7.5. Calcium behaved like magnesium, whereas the uptake of potassium and phosphorus was not affected by a low pH of the nutrient solution.

Schuffelen and Loosjes[57 58], working with an artificial colloid (dusarit = H_2SO_4-treated charcoal), found that the activity of the magnesium ions in such a medium was decreased by increasing the amount of adsorbed H-ions and particularly by increasing the amount of adsorbed K-ions. In short-term experiments with oat plants these authors obtained a considerably reduced uptake of potassium from media with colloids and K-H-acetates, respectively, with decreased pH.

Olsen[45] studied the uptake of Cl-, NO_3-, H_2PO_4- and K-ions at various pH levels by rye from single-salt solutions containing very low concentrations of these ions. The uptake of anions attained maximum values in the pH range 4.0–5.5. From 5.5 to 8.0 it was found to be considerably reduced due to competition with HCO_3-ions. When this competition was eliminated, maximum values for nitrate uptake were obtained between pH 4.0 and 8.0. For K-uptake maximum values were obtained between pH 5.0 and 8.0. The decreased values between pH 5.0 and 4.0 were found to be due to a competition with H-ions. With a five-fold increased K-concentration, maximum uptake took place between pH 4.0 and 8.0.

In contrast with the results obtained by Olsen[45], van den Honert and Hooymans[18] found a clearly reduced uptake of nitrate by maize in the pH range from 5 to 8. Since the decrease was independent of the nitrate concentration in the medium, these authors deny the influence of HCO_3-ions and assume that the pH affects in some way the ion-carrier mechanism.

Mc Evoy[31] analyzed tobacco plants grown in sand culture at different levels of ammonium and sulphate supply. The nitrogen level of all media was kept constant by adding nitrate. Ammonium plants were found to be higher in nitrogen and phosphorus, slightly lower in potassium, but considerably lower in calcium and magnesium than nitrate plants. A high sulphate supply decreased the calcium and magnesium contents but did not affect the uptake of N, P and K. Almost similar results for Mg- and Ca-uptake were obtained by Bolle-Jones[5] in sand-culture experiments with *Hevea brasiliensis*. Laminae of nitrate plants were found to be considerably higher in Mg and Cal than those of ammonium plants. No effect of nitrogen compound on N-, P- and K-contents was observed by this author. With increasing amounts of added nitrate, magnesium content of the laminae was enhanced when the calcium content of the nutrient medium was low. At a high Ca-level Mg-content of the laminae was not affected by an increased nitrate concentration, but calcium content was slightly enhanced. Russell *et al.*[60] studied the effect of increasing amounts of applied ammonium nitrate on the minera composition of brome grass grown under field conditions. K-, Mg- and P- but not Ca-content was increased by the N-dressings. An increased uptake of Mg- and K-ions by oat plants from ion-exchange resins when the amounts of added nitrate were increased, was observed by Welch *et al.* [67]. In the case of citrus and radish such a relationship was not observed.

Scharrer and Jung [52 53] carried out extensive sand-culture experiments with wheat, perennial rye grass and sunflower. Nitrogen was applied at different rates as nitrate and ammonium compounds, respectively. In additional series P, K, Na, Ca and Mg were varied. The plants were harvested in a green stage and analyzed for N, P, S, K, Na, Ca and Mg. In agreement with the results obtained by earlier workers a beneficial effect of nitrate on uptake of cations and of ammonium on uptake of anions was found to exist. These authors stress the constancy of the sum of absorbed cations at a constant nitrate supply and of the sum of absorbed anions at a constant NH_4-supply. An increased uptake of a certain cation resulting from an increased concentration of the latter in the external medium was found to bring about a reduced uptake of other cations; the same was true of anion uptake (see also Bear *et al.* [4] and van Itallie [21 22]). Of the cations, potassium takes a somewhat exceptional place as its uptake was not affected by an increased concentration of Na, Ca, or Mg in the external solution, whereas an increased concentration of potassium strongly reduced the uptake of the other cations.

Gouny [16] found considerably higher values for absorbed potassium, calcium and magnesium in maize and lupine plants dressed with nitrate than in ammonium plants. Nitrogen and phosphorus contents were lowest in the nitrate plants.

A beneficial effect of nitrogen fertilization on magnesium nutrition of apple trees growing under natural conditions has been observed by some authors [6, 17].

A potassium-magnesium antagonism has been observed by many authors [7 13 20 28 27 34 35 58 65 66]. An excess of potassium in the nutrient medium is apparently frequently the cause of the occurrence of magnesium deficiency under natural conditions. Ferrari and Sluijsmans [13] made the important observations that not only did a high concentration of K-ions in the soil depress Mg-uptake, but also that a higher concentration of magnesium within the plant was required to eliminate magnesium-deficiency symptoms when the internal concentration of the K-ions was at a high level. There is some indication that the potassium-magnesium antagonism is more important in trees than in crop plants [7 34 35 65]. In *Aspergillus niger* it does not occur [41 43].

EXPERIMENTAL METHODS

Wheat, oats, maize and potatoes were grown in field experiments on slightly acid sandy soils with different levels of added nitrogen in the form of calcium or sodium nitrate, ammonium nitrate and ammonium sulphate, respectively. The soils used for these experiments were moderately poor in available magnesium as determined by the *Aspergillus niger* technique.

Similar experiments with wheat and oats were conducted in glass jars of approximately 2.5 l capacity.

To compare the uptake of nitrogen and magnesium applied simultaneously to the same roots and to different roots, use was made of glass jars divided by a glass plate in two halves. One half of the pot was filled with a soil, moderately poor in magnesium, the other half with a sand-peat mixture free from magnesium. Nitrogen in the form of nitrate or of an ammonium compound was added to the soil or to the sand-peat mixture.

Magnesium was determined colorimetrically with titan yellow [51] and biologically with *Aspergillus niger* [36 37 41 61].

RESULTS

a) Pot experiments with different nitrogen compounds (cereals)

Wheat plants, *var.* van Hoek, were grown in glass jars containing approximately 2 kg of a sandy soil, moderately deficient in available magnesium, pH (H_2O) 5.2. Nitrogen in the form of ammonium sulphate, ammonium nitrate and sodium nitrate was applied in amounts of 175, 350, 700, 1400 and 2100 mg N per pot, respectively. Plants dressed with magnesium received 0.4 g $MgSO_4 \cdot 7H_2O$ per pot.

The symptoms of magnesium deficiency appeared at a young stage. They were more pronounced in the plants dressed with ammonium sulphate than in those with ammonium nitrate. The higher the dose of ammonium compound applied, the heavier the symptoms of magnesium deficiency in the wheat plants (see Plates I–III). With sodium nitrate no symptoms of magnesium deficiency occurred. When magnesium sulphate had been applied, no magnesium-deficiency symptoms were observed in the plants dressed with sodium nitrate or ammonium nitrate, but pronounced symptoms occurred when ammonium sulphate was applied at the higher rates.

The yield data of this experiment were in agreement with the appearance of the wheat plants. The yields of the plants dressed with sodium nitrate were practically unaffected by the added magnesium in contrast with those of the plants dressed with ammonium sulphate or ammonium nitrate. When magnesium deficiency was eliminated, ammonium nitrate gave higher yields than sodium nitrate. The cause of this difference is unknown.

A similar experiment was carried out with oats. In this case Mitscherlich pots containing 7 kg of soil were used; nitrate was added as calcium and ammonium nitrate, respectively. The results of the latter experiment are plotted in Fig. 1. They are in agreement with those of the preceding experiment.

The soil-pH values of the latter experiment determined at the end of the growing period of the oats, are recorded in Table I. It will be seen that a pronounced acidification had resulted from the treatment with ammonium salts. Although the increased concentration of

TABLE I

Effect of nitrogenous fertilizers on soil pH*

	No added magnesium			1 g $MgSO_4 . 7H_2O$ per pot		
N, g per pot	$Ca(NO_3)_2$	NH_4NO_3	$(NH_4)_2SO_4$	$Ca(NO_3)_2$	NH_4NO_3	$(NH_4)_2SO_4$
0	4.6	4.6	4.6	4.7	4.7	4.7
0.35	4.7	4.6	4.1	4.6	4.5	4.0
1.05	4.9	4.5	3.7	4.9	4.4	3.9
2.10	5.0	4.3	4.1	5.1	4.3	3.8

* In this and all subsequent experiments of this paper, pH of the soil was measured in an aqueous suspension (1 : 5).

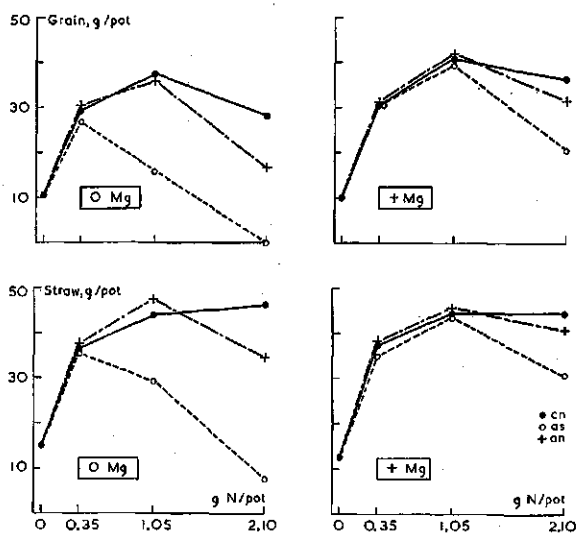
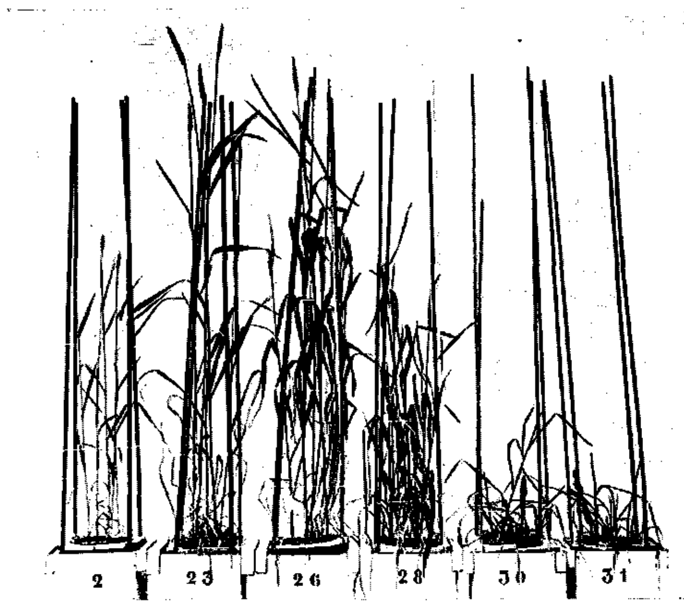


Fig. 1. *Effect of different amounts of added nitrogen in the form of calcium* nitrate (cn), ammonium nitrate (an), and ammonium sulphate (as) on the yield of oats, *var.* Marne, grown in Mitscherlich pots without added magnesium and in the presence of 1 g $MgSO_4 \cdot 7H_2O$ per pot. Basal dressing: 1.5 g K_2SO_4, 1.5 g $Ca(H_2PO_4)_2$ and 0.15 g $CuSO_4 \cdot 5H_2O$ per pot.

A



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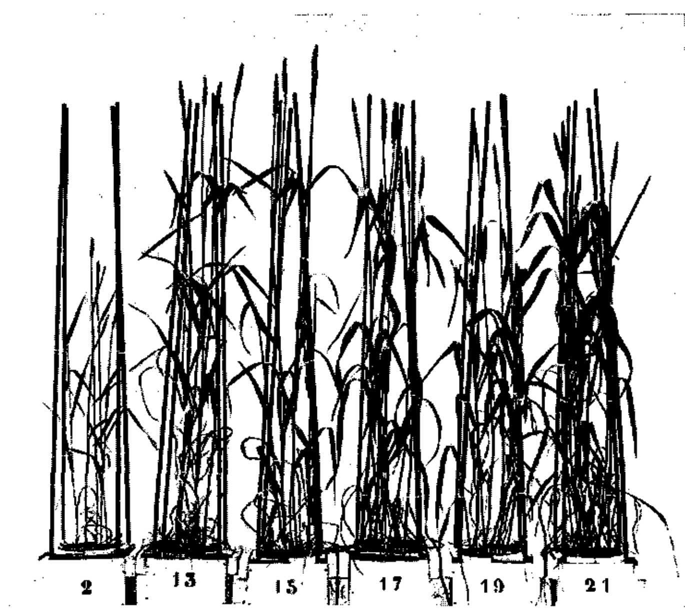
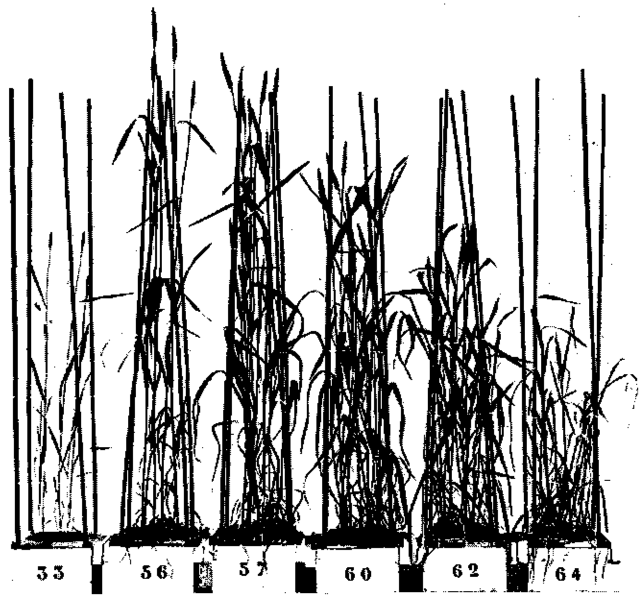


Plate I. Effect of different amounts of added nitrogen on the growth of spring wheat. From left to right: 0, 175, 350, 700, 1400 and 2100 mg N per pot. *No magnesium added.* A: N in the form of ammonium sulphate, B: N in the form of sodium nitrate.

A



B

Plate II. Effect of different amounts of added nitrogen on the growth of spring wheat. From left to right: 0, 175, 350, 700, 1400 and 2100 mg N per pot. *0.4 g* $MgSO_4.7H_2O$ *added per pot.* A: N in the form of ammonium sulphate, B: N in the form of sodium nitrate.

A

B

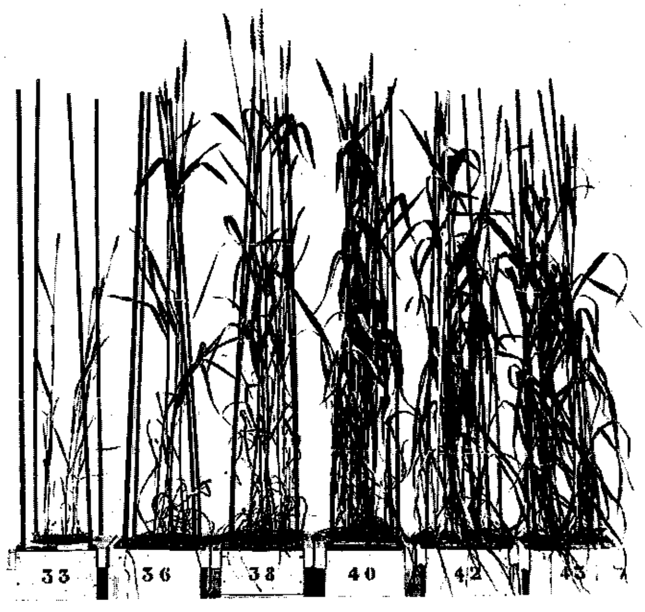


Plate III. Effect of different amounts of added nitrogen on the growth of spring wheat. From left to right: 0, 175, 350, 700, 1400 and 2100 mg N per pot. N in the form of ammonium nitrate. A: no magnesium added, B: 0.4 g $MgSO_4.7H_2O$ per pot.

H-ions in the soil has undoubtedly contributed to the occurrence of magnesium deficiency in the oat plants dressed with ammonium salts, the antagonizing effect of the NH_4-ions has presumably also played an important role in the reduced uptake of Mg-ions. In contrast to the latter, NO_3-ions exert a highly stimulatory effect on uptake of magnesium ions by higher plants. This is shown in the experiment of section *b*.

b) Pot experiment with divided root systems (cereals)

In order to demonstrate the beneficial effect of nitrate on magnesium uptake by wheat plants, the following pot experiment was carried out. Glass cylinders of 2.4 l capacity were divided by a vertical glass plate in two halves. One half of each pot was filled with a sandy soil of pH 5.1, the other half with a mixture of 9 parts quartz sand and 1 part peat, pH 6.3. The latter materials had been purified from magnesium by washing with sulphuric acid and glass-distilled water. The soil contained approximately 50 μg magnesium per 3 g of air-dried soil as determined by the *Aspergillus niger* method. This amount is too low when ammonium sulphate is used as the nitrogen source but may be sufficient for normal plant growth when nitrate is supplied.

The basal nutrients, 0.5 g K_2SO_4, 0.5 g $Ca(H_2PO_4)_2$ and 50 mg of $CuSO_4 \cdot 5H_2O$, were evenly distributed in both halves.

Nitrogen in the form of ammonium sulphate, ammonium lactate and calcium nitrate, respectively, was mixed either with the soil or with the sand-peat mixture. Magnesium sulphate, if supplied, was only given to the soil half of the pot. Six wheat seedlings were planted on top of the glass plate in such a way, that some of their roots grew into the soil and the others into the sand-peat mixture. This allowed a comparison to be made of the absorption of nitrogen (applied as ammonium or nitrate) and magnesium, when these elements were fed together to the roots or separately to different roots.

Symptoms of magnesium deficiency in the wheat plants became vizible shortly after the emergence of the second leaves. In the absence of added magnesium, healthy plants were found only in those pots where nitrate had been added to the soil half. When it had been given to the sand-peat mixture, which was completely free from magnesium, pronounced symptoms of magnesium deficiency occurred. The small amount of available magnesium present in the soil half of the pots, was apparently absorbed by the wheat roots only in those cases in which nitrate ions were absorbed simultaneously by the same roots. Plants supplied with ammonium lactate or ammonium sulphate showed pronounced symptoms of magnesium deficiency. Initially there was no difference between ammonium nitrogen supplied to the soil and to the sand. In the course of the growing period, however, the plants which had received ammonium lactate in the soil half improved their growth considerably. Presumably this was due to nitrate formation by nitrifying bacteria. In the case of ammonium sulphate, nitrate formation apparently did not occur, due to the more pronounced acidification of the soil.

Plants supplied with magnesium sulphate showed no symptoms of magnesium deficiency, and as with the plants growing without added magnesium, the best growth was obtained when nitrate and magnesium had been added to the same half pot.

The yield data of this experiment are given in Table II. They clearly show that nitrate exerted its beneficial effect only when it was given to the soil half of the pots which contained a small amount of available magnesium. When it was added to the sand-peat

TABLE II

Effect of different nitrogen compounds on yield of wheat plants grown with part of their roots in a magnesium-free sand-peat mixture and with the other part in a soil, moderately deficient in magnesium

N-compound applied	Half of the pot to which the N was added	$MgSO_4 \cdot 7H_2O$ added to the soil half, g	Yield *, g per pot		pH of soil after harvest	
			Grain	Straw	Soil half	Sand-peat half
$Ca(NO_3)_2$	soil	0	12.0	20.2	5.1	6.2
,,	sand-peat	0	4.0	13.1	4.8	6.7
NH_4-lactate	soil	0	8.1	16.9	4.9	6.1
,,	sand-peat	0	3.4	11.4	5.1	6.1
$(NH_4)_2SO_4$	soil	0	5.0	11.8	4.0	5.9
,,	sand-peat	0	4.6	12.3	4.6	5.1
$Ca(NO_3)_2$	soil	0.5	13.7	21.5	5.1	6.1
,,	sand-peat	0.5	10.4	17.9	4.6	6.5
NH_4-lactate	soil	0.5	11.6	17.8	4.6	6.1
,,	sand-peat	0.5	8.9	15.2	4.5	6.1
$(NH_4)_2SO_4$	soil	0.5	7.6	11.5	4.0	6.2
,,	sand-peat	0.5	8.7	13.5	4.5	5.2

* Averages of duplicate values.

mixture which was free from magnesium the yields were low, due to magnesium deficiency.

That the beneficial effect of nitrate on the magnesium uptake of the wheat plants was due to the NO_3-ions as such and not to the slightly reduced soil acidity may be concluded from the fact that magnesium was taken up from the soil at pH 4.9 in the presence of ammonium lactate more easily than at pH 5.1 in the absence of added nitrogen. In the former case NO_3-ions derived by nitrification from NH_4-lactate presumably were present in the soil.

To provide more evidence that the beneficial influence of nitrate on the magnesium supply was due to the NO_3-ions as such, a similar experiment was carried out in which an amount of $CaCO_3$, equivalent to that of the $Ca(NO_3)_2$ used, was added to the soil half of some of the pots. The pH values of the soil and the sand-peat mixture were 5.3 and 5.2 respectively.

The results of this experiment were in agreement with those of the preceding one: healthy plants when calcium nitrate was added to the soil half of the pot, magnesium-deficient plants when it was added to the sand-peat mixture. In the latter case it was of minor importance whether or not calcium carbonate had been mixed through the soil half.

c) *Field experiments with cereal crops*

The interaction between magnesium and nitrogenous compounds as observed in the pot experiments of sections *a* and *b* was also studied in field experiments with wheat, oats and maize. The moderately acid sandy soils used in these experiments were low in available magnesium as determined by the *Aspergillus niger* method.

Experiment 662

This experiment was started in 1942 on a sandy soil containing 6% organic matter, $pH(H_2O)$: 5.3; it was continued until 1949. Nitrogen was added in different amounts in the form of ammonium sulphate, calcium nitrate and ammonium nitrate limestone, respectively. A number of plots were dressed with magnesium sulphate every year, the others remained without a magnesium dressing. Those plots dressed with ammonium sulphate in one year, received nitrate in the next. Ammonium nitrate limestone only was applied every year to one series of plots.

1942, spring wheat. Nitrogen was applied in amounts of 30, 60, 90, 120 and 150 kg N per ha in the form of ammonium sulphate, ammonium nitrate limestone and calcium nitrate, respectively. As a basal dressing 80 kg P_2O_5 as $CaHPO_4$, 120 kg K_2O as KCl and 100 kg $CuSO_4 \cdot 5\ H_2O$ per ha were applied.

In agreement with the results of the pot experiment described in section *a*, no symptoms of magnesium deficiency in the wheat plants were observed when calcium nitrate had been used as the nitrogenous fertilizer. With ammonium nitrate limestone slight symptoms occurred at a young stage particularly at the highest nitrogen rates. The most pronounced deficiency symptoms were obtained with ammonium sulphate, however.

The yield data of this experiment are plotted in Fig. 2.

They clearly show the great effect of the nitrogen compounds on the response of the wheat plants to the magnesium dressing.

1943, winter wheat. In 1943 the experiment was continued with winter wheat. In contrast to the spring wheat of 1942, the winter wheat in 1943 hardly responded to the added magnesium. It is uncertain whether this was due to different climatic conditions in the two years or to varietal differences in magnesium requirement or magnesium uptake.

1945, spring wheat. In 1945, spring wheat was again grown on this field. Ammonium sulphate was applied to the calcium-nitrate plots of 1944 and calcium nitrate to the ammonium-sulphate plots. As will be seen from the yield data of Fig. 2 there was a great difference in response to added magnesium between the plots which had been dressed for 4 years with ammonium nitrate limestone on the one hand and those with alternately calcium nitrate and ammonium sulphate on the other. The plots dressed with ammonium nitrate limestone gave considerably higher yields in the absence of added magnesium than those with ammonium sulphate and calcium nitrate. Apparently this was due to the fact that in the former the level of available magnesium was maintained more satisfactorily than with nitrate and ammonium sulphate *. In the years with a nitrate dressing the removal of magnesium by the crop was favoured while in the years with ammonium sulphate a decrease of soil pH

* For the figures of available magnesium see the paper by Mulder and Hussain Aleem[48].

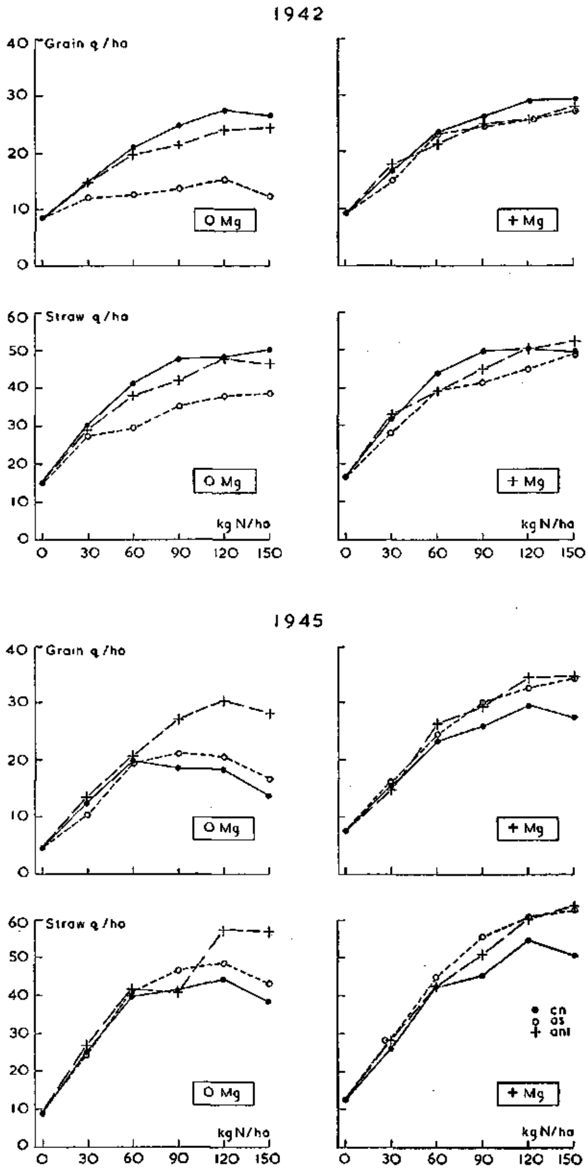


Fig. 2. Field experiment 662. Effect of different amounts of fertilizer nitrogen in the form of calcium nitrate (cn), ammonium sulphate (as), and ammonium nitrate limestone (anl) on the yield of spring wheat, *var.* van Hoek, grown without added magnesium and in the presence of 400 kg of $MgSO_4 \cdot 7H_2O$ per ha, respectively.

resulted in the leaching of magnesium by the autumn and winter rains (see Table III for the pH values).

Similar results to those of Experiment 662 have been obtained in a number of other field trials with oats and maize. The latter are recorded in section *e*. (Experiments 1312 and 1325, 1953).

d) Field experiments with potatoes

The results of a number of field experiments with potatoes have been plotted in Figures 3 and 4. In experiment 662, which was continued from 1942 to 1949, potatoes were grown in 1944, '46, '47, '48 and '49. Nitrogen in the form of calcium nitrate, ammonium nitrate limestone and ammonium sulphate, respectively, was applied at the rate of 50, 100, 200 and 300 kg of N per ha. Equal amounts were applied on the same plots every year. The ammonium nitrate limestone was applied each year to the same plots but calcium-nitrate and ammonium-sulphate dressings were interchanged on the other plots every year. The latter procedure effected a greater loss of soil magnesium than the manuring with ammonium nitrate limestone (a higher removal of Mg by the crop in the years with nitrate dressing and a more pronounced acidification followed by an increased leaching by the rains during the autumn and winter in a year with ammonium-sulphate application). Yet ammonium sulphate gave consistently lower yields than nitrate, apparently due to the antagonizing effect of ammonium ions and the beneficial effect of NO_3-ions on magnesium uptake (see Fig. 3). The pH values of the soil of this experiment have been recorded in Table III.

TABLE III

Effect of nitrogenous fertilizers on the pH(H_2O) of the soil * (Exp. 662)

Kg N per ha †	1942			1943			1944			1945			1947			1948		
	cn§	as§	anl§	as	cn	anl	cn	as	anl	as	cn	anl	as	cn	anl	cn	as	anl
0	5.2	5.2	5.2	5.2	5.2	5.2	5.3	5.3	5.3	5.3	5.3	5.3	5.0	5.0	5.0	5.3	5.3	5.3
50 (30)	5.2	5.2	5.2	5.2	5.4	5.3	5.2	5.1	5.2	5.2	5.1	5.2	4.8	4.9	5.0	5.2	5.1	5.3
100 (60)	5.2	5.1	5.2	5.1	5.2	5.2	5.1	4.9	5.1	5.1	5.0	5.1	4.6	4.8	4.9	5.3	5.1	5.2
150 (90)	5.3	5.1	5.3	5.1	5.2	5.3	5.2	4.8	5.2	5.1	5.0	5.2	4.6	4.8	5.0	5.2	5.0	5.3
200 (120)	5.2	5.0	5.2	5.0	5,3	5.3	5.1	4.7	5.2	5.0	4.9	5.2	4.4	4.7	5.0	5.2	4.8	5.3
300 (150)	5.3	4.9	5.2	4.9	5.2	5.2	5.2	4.6	5.1	5.0	4.9	5.1	4.3	4.5	4.8	5.0	4.8	5.3

* Measured by quinhydrone electrode; average values of 0 Mg and + Mg plots.

† N-rates supplied to potatoes; in parentheses: N-rates of cereals. Potatoes grown in 1944, '46, '47, '48 and '49, wheat in 1942, '43 and '45.

§ cn = calcium nitrate, as = ammonium sulphate, anl = ammonium nitrate limestone. The cn- and as-dressings interchanged each year, those with anl were applied each year on the same plot.

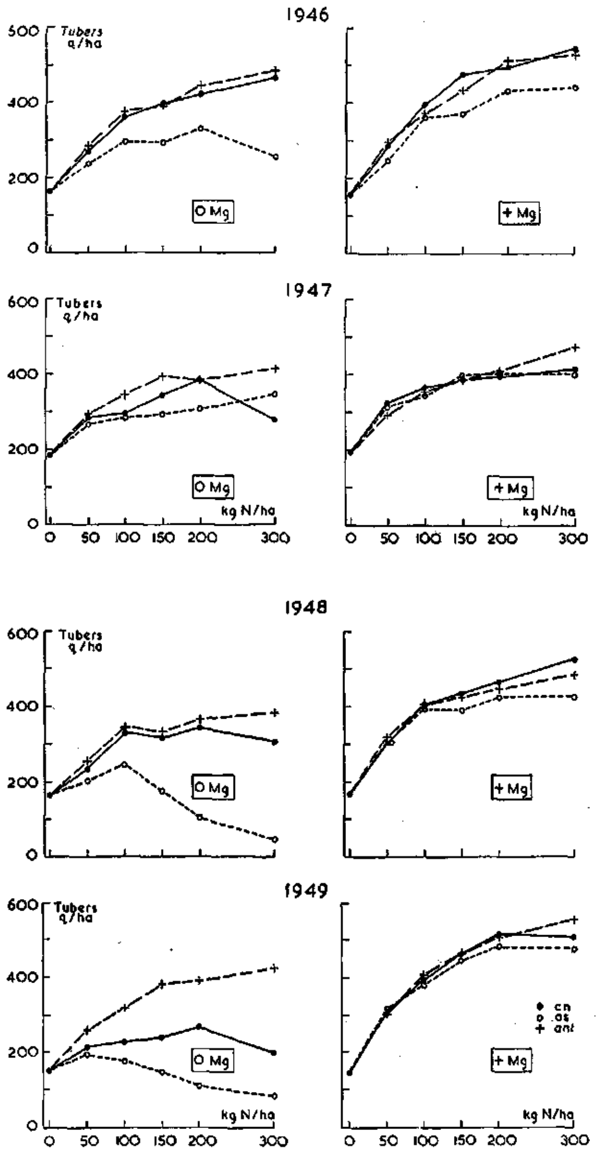


Fig. 3. Field experiment 662 (potatoes, *var.* Voran). Effect of different amounts of fertilizer nitrogen in the form of calcium nitrate (cn), ammonium sulphate (as), and ammonium nitrate limestone (anl) on the yield of potatoes grown without added magnesium and in the presence of 200 kg of $MgSO_4 \cdot H_2O$ per ha, respectively. All plots received a basal dressing of 100 kg P_2O_5 per ha as double superphosphate, and 300 kg K_2O per ha as K_2SO_4.

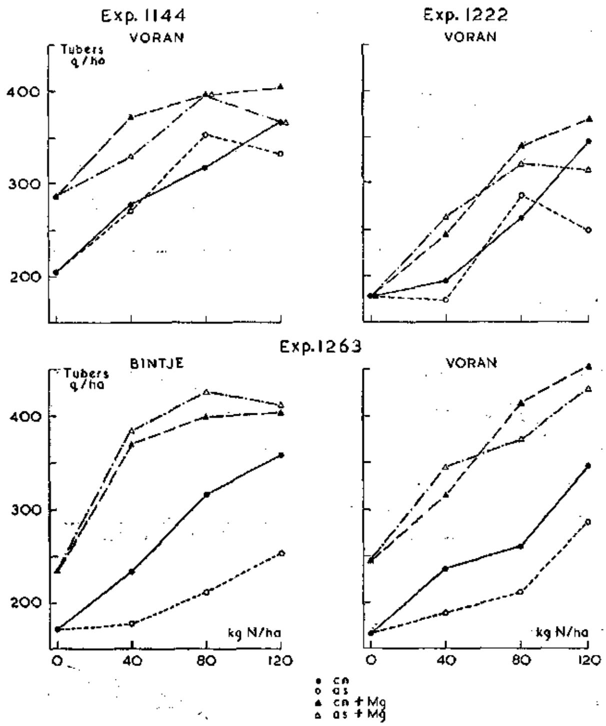


Fig. 4. Effect of different amounts of fertilizer nitrogen in the form of calcium nitrate (cn) and ammonium sulphate (as) on the yield of potatoes grown without added magnesium and in the presence of 150 kg $MgSO_4 \cdot H_2O$ per ha, respectively.

These experiments were laid out on sandy soils, adequately supplied with P and K (100 kg P_2O_5 per ha in the form of superphosphate, and 200 kg K_2O per ha as K_2SO_4). Exp. 1144: soil pH 5.1, organic matter 4.8%; Exp. 1222: pH 4.7, organic matter 7.1%; Exp. 1263: pH 5.0, organic matter 4.2%.

The results of a few further field experiments with potatoes are plotted in Fig. 4. These results demonstrate the favourable effect of nitrate on magnesium uptake by the potato plants; they are in agreement with those of the pot experiments with wheat plants which had divided root systems (see section *b*). In the presence of added magnesium the nitrate-yield curves have their steepest rise between 0 and 80 kg N (Exp. 1222) or between 0 and 40 kg (Experiments 1144 and 1263 *var.* Bintje). With greater amounts of added nitrogen the curves flatten, indicating that the N-supply is approaching its optimum. In the absence of added magnesium, however, the nitrate-yield curves continue to rise steeply up to the highest N-level. Since it may be assumed that the N-supply to magnesium-deficient and magnesium-dressed plants at the same nitrogen level is equal, it must be concluded that the rise in yield between 80 and 120 kg nitrate-N (Exp. 1222) and between 40 and 120 kg nitrate-N (Experiments 1144 and 1263 *var.* Bintje) in the absence of added magnesium is mainly due to the "magnesium effect" of $Ca(NO_3)_2$, *i.e.* to the improved magnesium uptake due to the presence of NO_3^--ions.

The effect of nitrate on magnesium uptake by potato plants is of general importance in growing potatoes on slightly acid sandy and peaty soils in the Netherlands. Frequently pronounced symptoms of magnesium deficiency occur when the nitrogen supply is low. Application of magnesium sulphate without improving the nitrogen supply often does not eliminate the magnesium-deficiency symptoms. An ample dressing of nitrate, however, often enables the plants to take up, even from soils relatively poor in available magnesium, adequate amounts of magnesium for a normal development. Ammonium nitrate limestone which is commonly used by the farmers as the nitrogenous fertilizer gives results comparable to those of calcium nitrate, due to its nitrate content and the nitrification of part of the ammonia. Magnesium deficiency symptoms *, magnesium content of the foliage, and yield of tubers may be used to demonstrate the effect of nitrate on magnesium uptake. Fig. 5 gives the results of a number of field experiments using increasing amounts of ammonium nitrate limestone, in the presence or absence of added magnesium sulphate. It will be seen that foliar symptoms of magnesium deficiency occurred in the presence of 80 kg of added MgO per ha when the nitrogen manuring was low. On the other hand, healthy plants were mostly obtained at the rate of 140 kg N per ha in the absence of added magnesium. The magnesium content of the foliage (Fig. 6) and the yield of tubers (Fig. 5) responded in a similar way to the nitrogen manuring.

e) Direct effect and after-effect of N-compounds on the magnesium supply of plants

In order to compare the direct effect (mainly caused by the kind of N supplied) and after-effect (mainly caused by change of soil pH) of a single manuring with ammonium sulphate or calcium nitrate,

* Foliar symptoms of magnesium deficiency have been evaluated by K. Boskma in the middle of July.

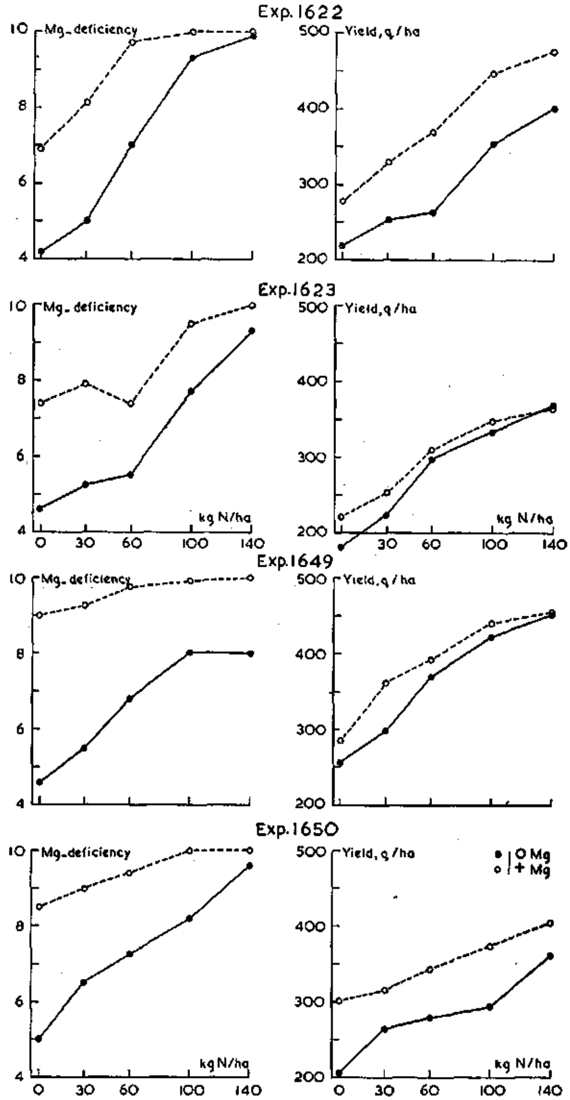


Fig. 5. Effect of increasing amounts of added ammonium nitrate limestone on magnesium-deficiency symptoms in the foliage (left) and on the yield (right) of potatoes, *var.* Voran, grown in the absence of added magnesium and in the presence of 300 kg $MgSO_4 \cdot H_2O$ per ha. 4 = pronounced symptoms of Mg-deficiency, 10 = healthy plants.

Soil pH: 5.4 (Exp. 1622), 5.6 (Exp. 1649), and 4.9 (Exp. 1650). Soil organic matter (%): 4.0 (Exp. 1622), 4.8 (Exp. 1649), and 12.0 (Exp. 1650). A basal dressing of 120 kg P_2O_5 per ha as double superphosphate and 160–200 kg K_2O per ha as K_2SO_4 was applied.

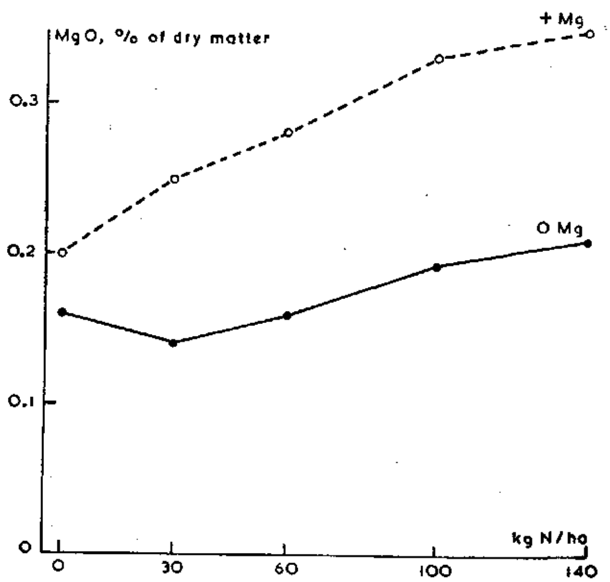


Fig. 6. Effect of different amounts of nitrogen as ammonium nitrate limestone on magnesium content of the foliage of potatoes, *var.* Voran (average samples of stems and leaves). Exp. 1622 (see Fig. 5). + Mg = 80 kg MgO per ha as $MgSO_4 \cdot H_2O$.

on magnesium nutrition of crop plants, experiments 1312 and 1325 were started in 1952. These experiments were carried out on acid sandy soils (organic matter 4.0 and 4.2% and pH, H_2O, 5.0 and 4.8, respectively).

The design of these experiments was as follows. One set of plots (A) received each year 1952–1955 nitrogen in the form of calcium nitrate or ammonium sulphate. The different plots of the series received different levels of N-supply each year. A second set (B) received similar dressings once in two years (1952, 1954), and a third (C) once in three years (1953). In the years that no calcium nitrate or ammonium sulphate was supplied, a uniform dressing of ammonium nitrate was given to all plots, except to the nil-nitrogen plots. Magnesium, if supplied, was applied only in those years when ammonium sulphate and calcium nitrate were given. In the autumn of the second year calcium carbonate free from magnesium was supplied to the ammonium-sulphate plots at the rate of 1 kg $CaCO_3$ per kg of total amount of $(NH_4)_2SO_4$ applied in 1952 and 1953. Potatoes were grown in 1952 and 1955 maize in 1953, and oats in

1954. All plots received every year a basal dressing of 100 kg P_2O_5 per ha (to cereals) or 120 kg P_2O_5 per ha (to potatoes) as double superphosphate, and 120 kg K_2O per ha as KCl (to cereals) or 250 kg K_2O per ha as K_2SO_4 (to potatoes). The results of these experiments

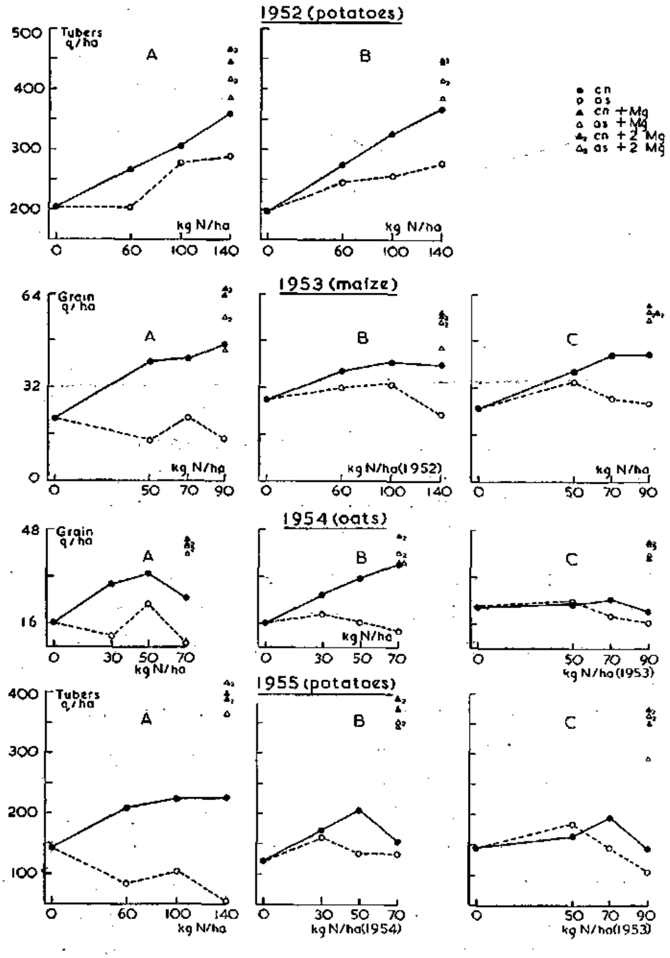


Fig. 7. Experiment 1312. Effect of different amounts of nitrogen in the form of ammonium sulphate (as) and calcium nitrate (cn) on the yield of potatoes (*var.* Voran), maize (*var.* Goudster), and oats (*var.* Zege). *A*: dressed every year, *B*: dressed in 1952 and 1954, and *C*: dressed in 1953 only, with as, cn and Mg according to plan.

In the years when no calcium nitrate and ammonium sulphate were supplied the B and C plots, except the nil-N plots, were dressed uniformly with ammonium nitrate (70 kg N per ha in the case of cereals and 140 kg N per ha on potatoes. Magnesium, when supplied, was given to the plots with the highest N-rate in amounts of 40 (Mg) and 80 (2 Mg) kg MgO per ha in the form of $MgSO_4 . H_2O$.

are plotted in Figures 7 and 8. They are in general agreement with those of the experiments described in sections *a* and *b*, viz. a considerably more pronounced response to magnesium on the plots dressed with $(NH_4)_2SO_4$ than on those dressed with $Ca(NO_3)_2$. The pH values are given in Table IV.

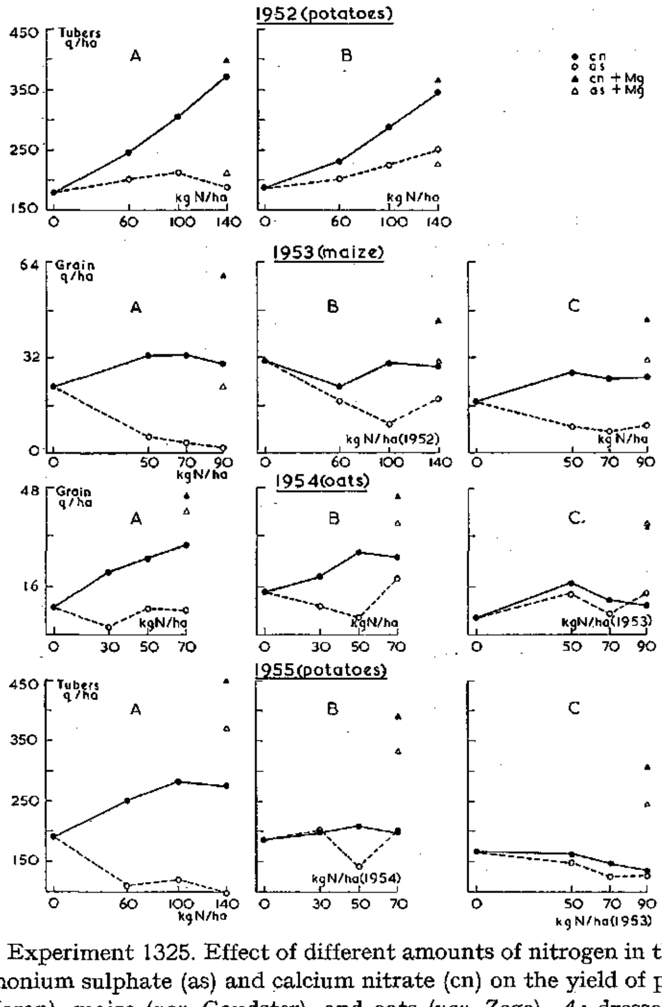


Fig. 8. Experiment 1325. Effect of different amounts of nitrogen in the form of ammonium sulphate (as) and calcium nitrate (cn) on the yield of potatoes (*var.* Voran), maize (*var.* Goudster), and oats (*var.* Zege). *A*: dressed every year, *B*: dressed in 1952 and 1954, and *C*: dressed in 1953 only, with as, cn and Mg according to plan.

In the years when no calcium nitrate and ammonium sulphate were supplied the B and C plots, except the nil-N plots, were dressed uniformly with ammonium nitrate (70 kg N per ha in the case of cereals, and 140 kg N per ha on potatoes). Magnesium, when supplied, was given to the plots with the highest N-rate in an amount of 40 kg MgO per ha in the form of $MgSO_4.H_2O$.

TABLE IV

Direct effect, after-effect and cumulative effect of calcium nitrate and ammonium sulphate on pH (H_2O) of the soil * (Experiments 1312 and 1325)

Exp., year and crop	A Cn and as in 1952, '53, '54, '55			B Cn and as in 1952, '54			C Cn and as in 1953		
	kg N per ha	cn	as	kg N per ha	cn	as	kg N per ha	cn	as
1312, 1952	0	4.9	4.9	0	4.9	4.9	0	—	—
potatoes	60	5.0	4.6	60	4.9	4.7	140 †	—	—
	100	5.0	4.7	100	5.0	4.7	140 †	—	—
	140	5.0	4.6	140	5.0	4.7	140 †	—	—
1312, 1953	0	4.8	4.8	0	5.0	5.0	0	4.8	4.8
maize	50	4.9	4.5	70 †	4.9	4.8	50	4.8	4.7
	70	4.9	4.6	70 †	4.8	4.7	70	5.0	4.6
	90	4.9	4.4	70 †	4.8	4.8	90	4.8	4.5
1312, 1954 §	0	4.8	4.8	0	4.8	4.8	0	4.8	4.8
oats	30	5.0	4.7	30	4.9	4.8	70 †	4.8	4.8
	50	5.0	4.8	50	4.9	4.8	70 †	4.9	4.7
	70	5.0	4.8	70	4.8	4.7	70 †	4.7	4.7
1312, 1955	0	4.7	4.7	0	4.8	4.8	0	4.6	4.6
potatoes	60	4.8	4.5	140 †	4.7	4.6	140 †	4.6	4.6
	100	4.8	4.7	140 †	4.7	4.6	140 †	4.6	4.6
	140	4.8	4.5	140 †	4.6	4.7	140 †	4.6	4.6
1325, 1952	0	4.7	4.7	0	4.9	4.9	0	—	—
potatoes	60	4.7	4.5	60	4.7	4.5	140 †	—	—
	100	4.8	4.4	100	4.7	4.4	140 †	—	—
	140	4.9	4.4	140	4.8	4.4	140 †	—	—
1325, 1953	0	4.8	4.8	0	4.9	4.9	0	4.8	4.8
maize	50	4.7	4.4	70 †	4.7	4.7	50	4.7	4.5
	70	4.8	4.4	70 †	4.7	4.6	70	4.7	4.4
	90	4.8	4.4	70 †	4.7	4.6	90	4.6	4.4
1325, 1954 §	0	5.0	5.0	0	4.9	4.9	0	4.9	4.9
oats	30	5.0	5.0	30	4.9	4.9	70 †	4.9	4.8
	50	5.0	4.9	50	5.0	4.9	70 †	4.9	4.8
	70	5.1	5.1	70	5.0	4.9	70 †	4.8	4.9
1325, 1955	0	4.6	4.6	0	4.7	4.7	0	4.6	4.6
potatoes	60	4.7	4.6	140 †	4.7	4.7	140 †	4.5	4.5
	100	4.7	4.6	140 †	4.6	4.7	140 †	4.5	4.6
	140	4.7	4.6	140 †	4.7	4.7	140 †	4.5	4.6

* Samples taken in the autumn; pH measured by quinhydrone electrode.

§ $CaCO_3$, practically free from magnesium, at the rate of 1 kg $CaCO_3$ per 1 kg $(NH_4)_2SO_4$, applied in 1952 and 1953, was given to the as-plots in December 1953.

† N in the form of NH_4NO_3.

In 1953 a comparison could be made between direct effect of ammonium sulphate and calcium nitrate (C plots), after-effect (B plots) and cumulative effect (A plots). Although the nitrogen rates in 1952 had been higher than those in 1953, owing to the higher N-requirement of potatoes than that of maize, the after-effect of an ammonium dressing (B plots) on magnesium supply of the maize plants was slightly less harmful than the direct effect of this N-compound (C plots). This was particularly true of Experiment 1325. When ammonium sulphate had been applied in two successive years (1952, 1953) practically no yield of maize was obtained in 1953. A dressing of 80 kg MgO per ha as magnesium sulphate gave a considerably improved plant growth, but the yields were still much lower than with calcium nitrate plus magnesium. In 1954 and '55 practically normal yields were obtained on the A-pots in the presence of added magnesium, demonstrating that the total failure of the oat crop in 1954 and the potato crop in 1955 in the absence of added magnesium was a result of an inadequate magnesium supply of the plants.

The harmful after-effect of a manuring with ammonium sulphate on the magnesium nutrition of a subsequent crop is presumably mainly due to an increased leaching of magnesium by the autumn and winter rains when the acidity of the soil is increased. In addition the high acidity may have an unfavourable effect on the uptake of magnesium ions by the plant roots.

The relationships 1) between Mg-supply to cereal plants and the pH of the nutrient medium in culture solution, and in sand respectively, 2) between Mg-supply to plants and the soil pH, and 3) between the soil pH and the available magnesium as determined by the *Aspergillus niger* technique, were studied in a previous paper [61]. An abstract of the main results of that paper will be given in the following pages.

1a. Plants growing in culture solutions

Oat plants were grown in nutrient solutions containing a range of amounts of added magnesium at pH 4.0–4.5 and pH 6.0–6.5, respectively. In the acid medium inadequate amounts of magnesium were found to give a somewhat greater depression of yield than in the sub-neutral medium.

This was presumably because the root systems of the plants in the acid medium, particularly at low magnesium levels, were initially considerably smaller than those of plants growing in the neutral medium. At a later stage these root systems more or less recovered. In order to see whether the uptake and assimilation of magnesium were affected by the pH of the nutrient medium, a small amount of magnesium sulphate was added to some of the magnesium-deficient cultures when the plants were two months old. The response to the added magnesium was found to be practically unaffected by the pH of the nutrient medium (see Table V).

TABLE V

Effect of magnesium supply and pH of culture solution on the yield *, g dry matter per pot, of oat plants

mg Mg per culture	pH 4.0—4.5		pH 6.0—6.5	
	Grain	Straw	Grain	Straw
0	0	0.15	0	0.40
0 + 1 †	0	0.29	0	1.90
0.26	0	0.47	0	2.58
0.26 + 2 †	0	3.24	0	3.14
1.35	0	3.50	0	5.40
1.35 + 3 †	1.22	5.73	0	8.24
105	6.66	9.80	8.17	12.07

* Averages of duplicate values. † Added after 2 month's growth.

1b. Oat plants growing in sand-peat mixtures

Both the sand and the peat had been purified from magnesium. $CaCO_3$, free from magnesium, was applied in amounts of 0, 1, 2, 3 and 5 g per jar containing 2 kg of sand-peat mixture (10 sand : 1 peat). Magnesium was applied in amounts of 0, 5, 10 and 50 mg Mg, respectively, in the form of $MgSO_4 \cdot 7H_2O$. Only the 0- and 10-mg series were supplied with the highest dose of $CaCO_3$.

At pH values of 3.5 and 4.2 no normal growth of the oat plants in the sand-peat medium took place; the response to added magnesium was slight at these pH values (see Table VI). At pH values of 4.6, 5.6 and 6.8 a pronounced response to added magnesium was found to occur. When a comparison is made between the yield data at pH 4.6 and those at pH 5.6, it will be seen that the response to magnesium was approximately equal in both cases.

TABLE VI

Effect of magnesium supply and pH of the medium on the yield *, g dry matter per pot, of oat plants grown in sand-peat mixtures

mg Mg per pot	$CaCO_3$, g per pot									
	0 (3.5) †		1 (4.2)		2 (4.6)		3 (5.6)		5 (6.8)	
	grain	straw	grain	straw	grain	straw	grain	straw	grain	straw
0	0	0.08	0	1.07	0	8.51	0.70	10.06	0.75	11.59
5	0	0.17	0	2.00	6.07	12.42	8.58	15.83	—	—
10	0	0.12	0	2.51	8.13	12.26	11.57	16.06	13.14	17.10
50	0	0.12	0	3.74	12.87	14.12	17.73	15.46	—	—

* Averages of duplicate values.

† In parentheses: pH values, average values of 0- and 10-mg Mg series.

2. Plants growing in soil

Oat plants were grown in acid magnesium-deficient sandy soils with and without added $CaCO_3$. The effect of added $MgSO_4$ was investigated on the acid soils and on $CaCO_3$-treated soils.

Although the response of the oat plants to magnesium (in the absence of added $CaCO_3$) was considerably more pronounced than that to $CaCO_3$ (in the absence of added magnesium), the latter treatment gave a clearly improved plant growth (see Table VII). Since available magnesium, as determined by the *Aspergillus niger* technique, was found to be not affected by the liming of the acid soils, it must be concluded that the reduced acidity of the soil had to some extent favoured the uptake of the small amount of available magnesium present in the acid soils. This may have been due both to a better developed root system and to an improved uptake of Mg-ions under less acid conditions. An increased nitrification and a stimulation of magnesium uptake by the nitrate (see section *b*) may also have played a part.

TABLE VII

Effect of $MgSO_4$ and $CaCO_3$ on the yield, g dry matter per pot, of oats grown in acid sandy soils

Soil *	pH (H_2O)	Grain	Straw
Z, control	4.1	0	2.66
Z, + $MgSO_4$ †	—	5.88	5.55
Z, + $CaCO_3$ †	—	3.42	5.41
Z, + $MgSO_4$ + $CaCO_3$	—	6.88	6.00
R, control	4.6	0.88	5.28
R, + $MgSO_4$	—	10.08	9.00
R, + $CaCO_3$	—	4.75	7.31
A, control	5.4	5.14	5.43
A, + $MgSO_4$	—	7.32	6.72
A, + $CaCO_3$	—	6.53	6.38
A, + $MgSO_4$ + $CaCO_3$	—	7.57	6.40
W, control	4.8	0	0.93
W, + $MgSO_4$	4.7	9.27	9.10
W, + $CaCO_3$	7.1	0.85	6.65
W, + $MgSO_4$ + $CaCO_3$	6.9	11.24	11.40

* Glass jars containing 0.5 (Z), 1 (R) and A) and 1.75 (W) kg of soil were used.

† $MgSO_4 \cdot 7H_2O$ and $CaCO_3$, were applied in amounts of 0.75 and 2.0 g per kg of soil. In the case of soil W these amounts were 0.57 and 2.9 g.

3. Soil pH and plant-available magnesium

To study the relationship between soil pH, available magnesium in the soil and the degree of magnesium deficiency of cereal crops, the following experiments have been carried out. Soil samples were taken from different areas of magnesium-deficient fields, viz. from areas with severely magnesium-deficient plants, with moderately magnesium-deficient plants and with healthy plants, respectively. The appearance of the cereal plants, the content of available soil magnesium and the pH of the soil were determined. As will be seen from Table VIII a close correlation was found to exist between the soil pH, the content of available magnesium and the appearance of the crop.

TABLE VIII

Relationship between soil pH, available magnesium (*Aspergillus niger*) and status of oat crop

Soil	pH (H_2O) *	Status of the crop †	Available Mg, μg per 3 g of air-dried soil	Soil	pH (H_2O)	Status of the crop	Available Mg, μg per 3 g of air-dried soil
Z	4.1	D	<25	B	4.2	D	25
Z	4.6	SD	<25	B	4.3	SD	75
Z	5.5	H	200	B	4.7	H	150—200
E	4.2	D	25	V	4.4	D	25—50
E	4.5	SD	25	V	4.4	SD	100
E	5.8	H	75—100	V	5.0	H	150—200
K	4.5	D	25	Vd	5.0	D	<50
K	4.8	SD	25—50	Vd	5.7	SD	<50
K	5.2	H	150	Vd	5.2	H	<50
A	5.2	D	50	Vn	5.0	D	<25
A	5.6	SD	100	Vn	5.7	SD	50—100
A	5.8	H	150—200	Vn	6.1	H	150
R	4.6	D	25—50	T	5.2	D	50
R	4.8	SD	25—50	T	5.3	SD	100
R	4.9	H	100	T	5.1	H	100
L	4.4	D	50—100	He	5.2	D	25
L	4.8	SD	100	He	5.3	SD	50—75
L	4.8	H	200	He	4.7	H	75—100
O	4.4	D	25	Ha	4.2	D	<50
O	4.8	SD	50	Ha	4.3	SD	<50
O	4.9	H	100	Ha	4.7	H	75—100

* Measured by glass electrode.

† D = severely deficient, SD = slightly deficient, H = healthy plants.

The harmful effect of a low pH on the content of available soil magnesium was found to be due to an increased loss of magnesium by leaching. This was demonstrated by incubating for 2½ months a number of samples of a fertile sandy soil (approximately 20% organic matter) after acidification with increasing amounts of sulphuric acid to pH values of 4.1, 3.9, 3.6, 2.8 and 2.2, respectively. No decrease of available soil magnesium during this period was observed. When, however, the samples were leached with distilled water, until no further SO_4-ions occurred in the filtrate, nearly all of the available magnesium appeared to be lost.

Neutralization of an acid sandy soil by $CaCO_3$ did not affect the content of available magnesium.

From the results of these earlier experiments, which are recorded in more detail in Ref. [61], it may be concluded that the harmful after-effect of a dressing with ammonium sulphate upon the magnesium supply of the crop, as observed in Experiments 1312 and 1325, is partly due to loss of available magnesium during the wet autumn and winter following a summer season in which the ammonium sulphate was applied *. Since leaching of the soil does not take place during the summer, it must be concluded that the direct effect of ammonium sulphate on magnesium nutrition is due to an antagonizing effect of NH_4- and H-ions on Mg-uptake. The inhibiting effect of these ions on the development of the root system may also have played a role.

That the harmful after-effect of a manuring with ammonium sulphate is partly due to an increased leaching out of the plant-available magnesium may also be concluded from the field experiments 1084 and 1090. Ammonium sulphate and calcium nitrate were applied in 1949 at the rates of 40, 80 and 120 kg N per ha, in the absence and presence of added magnesium, respectively. In 1950 a uniform manuring of 120 kg N per ha in the form of ammonium nitrate was given to all plots. In both years potatoes were grown. In 1951, when maize was grown on Field 1084 and rye on Field 1090, a uniform dressing of 100 kg N per ha as NH_4NO_3 was given. A basal dressing of P and K was applied each year; magnesium, however, was only given in 1949.

The pH values of the NH_4- and NO_3-plots which differed significantly in the autumn of 1949 were almost equal at the end of 1950 (see Table IX). Notwithstanding the small differences in soil

TABLE IX

Effect of nitrogenous fertilizers on soil pH

Kg N per ha	1949				1950			
	no added Mg		+ Mg		no added Mg		+ Mg §	
	as	cn	as	cn	as §	cn §	as §	cn §
Exp. 1084								
0	5.2	5.2	5.1	5.1	5.3	5.3	5.2	5.2
40	5.0	5.0	4.9	4.9	5.1	5.2	5.0	5.2
80	4.7	5.1	4.6	5.0	5.0	5.1	5.0	5.2
120	4.6	5.0	4.7	5.0	5.2	5.2	5.1	5.4
Exp. 1090								
0	4.4	4.4	4.4	4.4	4.3	4.3	4.4	4.4
40	4.3	4.4	4.2	4.2	4.5	4.3	4.4	4.3
80	4.2	4.4	4.2	4.3	4.1	4.5	4.2	4.5
120	4.2	4.3	4.2	4.4	4.4	4.3	4.3	4.2

§ As, cn and Mg were applied in 1949 only.

* See also the paper by Mulder and Hussain Aleem [43].

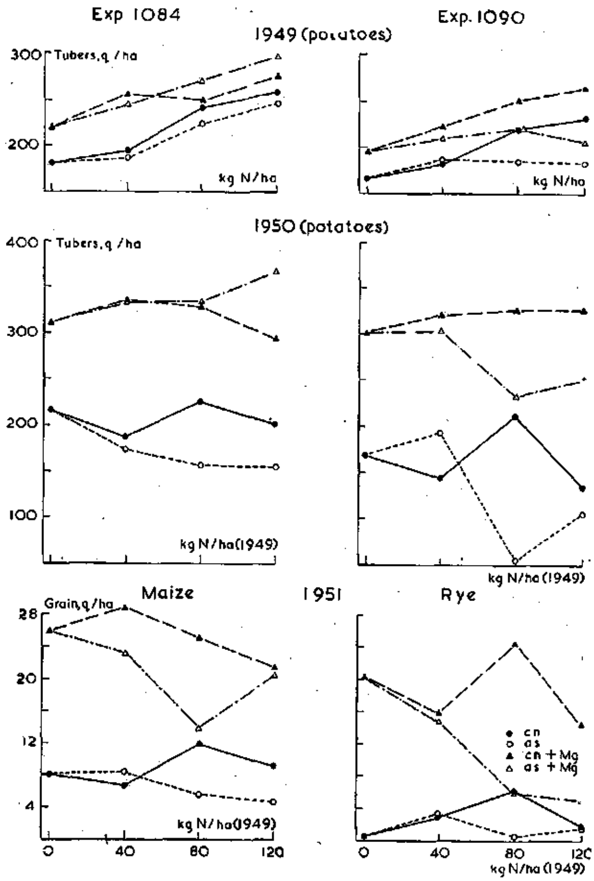


Fig. 9. Direct effect and after-effect of a manuring with calcium nitrate (cn) and ammonium sulphate (as) applied in 1949. In 1950 and 1951 a uniform dressing of ammonium nitrate was given to all plots (120 kg N per ha to the potatoes, 100 kg N per ha to the maize, and 80 kg to the rye). + Mg = 40 kg MgO per ha in the form of $MgSO_4 \cdot H_2O$, applied in 1949.

pH there was a pronounced difference in occurrence of magnesium-deficiency symptoms and in the yield of maize and rye in 1951 between plots dressed in 1949 with ammonium sulphate and those with calcium nitrate, respectively (see Fig. 9). This was not only true of the nil-Mg plots but also of the plots dressed in 1949 with 40 kg MgO per ha. A relatively large proportion of the magnesium, applied in 1949 had apparently been leached out of the soil on the plots dressed with ammonium sulphate in 1949.

DISCUSSION

From the results of the above investigations it may be concluded that the harmful effect of ammonium sulphate and the beneficial effect of nitrate on the magnesium nutrition of crop plants, growing under natural conditions, do not depend on a simple relationship. The following factors are assumed to be responsible for the observed phenomena.

a) Under humid conditions, such as prevail in large parts of Western Europe, a shift of the soil pH in an acid direction following a fertilization with ammonium sulphate will strongly promote the leaching of plant-available magnesium by the autumn and winter rains. This is particularly true when the pH falls below 5 approximately (see Table VIII and Ref. [43 61]). Under these conditions Mg-ions, adsorbed by soil colloids, are readily exchanged with H-ions so that they are subjected to leaching.

There is no indication that fixation of magnesium by the soil constituents, which may occur in certain soils [32 49] is a typical feature of light acid soils [61].

b) In addition to the effect on the soil, an increased H-ion concentration may effect the plant. Both the development of the root system and the functioning of the roots may be reduced by an increased acidity of the soil.

The effect of the pH of the nutrient medium on the uptake of inorganic nutrients in general and of magnesium in particular has been studied by a number of authors. Some of them have grown the plants for a considerable length of time in nutrient media, others have studied their uptake during a relatively short period of time. In the former case the pH may have affected the development as well as the functioning of the roots, in the latter the influence on the root development played no part. In the investigations of Arnon [2] (pH range from 5 to 6.7), Wadleigh and Shive [64] (pH range from 3 to 9), and Olsen [45] (pH range from 4 to 9) the effect of the pH of the nutrient medium on the uptake of inorganic nutrients from culture solutions was found not to be very pronounced. In short-term experiments with tomato, lettuce and Bermuda grass (pH range from 3 to 9), Arnon *et al.* [3] found a reduced uptake of P, K, Ca, and Mg, particularly of Ca, at pH 3 and 4. Michael [33] found a considerably reduced uptake of magnesium and calcium by maize and rye from nutrient solutions of pH 4 as compared with solutions of pH 6 or 7.5. No effect of pH on uptake of K and P was found. The rye experiment lasted 7 days, so that the effect of the pH on the root development in this case cannot have played an important role. Smit and Mulder [61] found a much more poorly developed root system in oats growing in a culture solution of pH 4–4.5 than at pH 6–6.5. There was not much difference in response to added magnesium between plants growing at these pH values. In sand-peat mixtures these authors found the growth of oats much curtailed at pH 3.5 and 4.2, irrespective of amount of added magnesium. At pH 4.6 the plants made normal growth in this medium and there was practically no difference in response to added magnesium between plants grown at pH 4.6, 5.6 and 6.8 (see Table VI).

From the results of these investigations on H-ion concentration, it may be concluded that the effect of low soil pH on magnesium uptake is not the main reason for the occurrence of magnesium deficiency in plants growing in acid soils. This conclusion is in agreement with the observation that addition of magnesium salts to such soils usually produces a healthy plant growth. That maximum yields are not always achieved by this treatment, when compared with Mg + lime, is not surprising, since other conditions, associated with a low soil pH (excess of Mn-ions, fixation of P, *etc.*) are not affected by $MgSO_4$, but are eliminated by liming. That a low soil pH may contribute, however, in the poor development of magnesium-deficient plants on soils already poor in available magnesium may be concluded from the results of Table VII (see also Ref. [61]). From these data it will be seen that mixing of the acid magnesium-deficient soils with $CaCO_3$ free from magnesium, gives an improved plant growth and an enhanced uptake of magnesium, without the content of available magnesium of the soil being affected. A possible explanation of this phenomenon is that a reduced acidity of the soil enables the plant to take up more magnesium owing to a better developed root system and (or) a better functioning of the roots (less competition of H-ions). The added $CaCO_3$ may also have increased the nitrification rate and in addition it may have eliminated other growth-limiting factors.

c) Of much more importance than the influence of the H-ion concentration of the nutrient medium (soil) on the uptake of magnesium is the effect of the kind of nitrogen source applied, ammonium or nitrate, on absorption and presumably assimilation of magnesium. In the case of ammonium nutrition the absorption of magnesium is strongly inhibited, whereas with nitrate as the nitrogen source it is strongly favoured (Figures 1, 2, 3 and Table II). Although in these experiments the pH of the soil was decreased by ammonium sulphate and slightly increased by nitrate treatment, it must be pointed out that the pH measurements were carried out after the plants had completed their growing period. At a young stage when only small amounts of nitrogen had been taken up by the plants and the resulting shift in pH of the soil was also small, the effect of the kind of nitrogen source applied on the magnesium supply was even more pronounced. This demonstrates that the effect of the nitrogen compound on magnesium uptake must to be sought within or on the surface of the plant roots rather than in the soil (see also the foregoing considerations under *b*).

The effect of applied nitrogen compound on uptake of other inorganic nutrients has also been observed by a number of other workers [2 5 16 31 52 53 64]. In general it was found that plants grown in a nitrate medium were higher in cations (K, Ca, Mg) than those grown in an ammonium medium. Conversely, the content of S and P was often higher in NH_4-plants than in nitrate plants. Of the cations, uptake of Ca and Mg was found in a number of cases to be more clearly affected by the nitrogen compound applied than that of K [5 31].

To explain the observed phenomena, it must be realized that the form in which the nitrogen is absorbed by the plant roots, cation or anion, has a dominating effect on the ratios

$$\frac{\text{absorbed } NH_4\text{-ions}}{\text{sum of absorbed other cations}} \text{ and } \frac{\text{absorbed } NH_4\text{-ions}}{\text{absorbed Mg-ions}}$$

in view of the large amount of nitrogen used by the plant. Values well above 1 may be found for the former ratio and above 10 for the latter, in plants dressed with an ammonium compound and growing in a medium in which no nitrification occurs.

A further point of interest is that in most plant tissues the absorbed ammonium ions soon after their entrance into the cytoplasm are assimilated into organic N-compounds. This involves an exchange with H-ions within the cytoplasm. As a result a high concentration of hydrogen ions will be found in the outer root cells of plants supplied with ammonium compounds.

Nightingale[44] growing dormant N-absorbing apple trees in a sand-culture medium with constant renewal at the rate of 36 l per 24 h at pH 6.0 with ammonium sulphate as the sole N-compound, found pH-values of 4.0–4.5 at the absorbing surface and tips of the fine fibrous roots. In a preliminary experiment in which the ammonium concentration was higher, pH values of 2.8–3 were found by this author at the root surface and the outer corticial cells. In the latter case the roots were abnormal, due to the high acidity. When the mean pH of the root tissues was measured, no difference was found between nitrate and ammonium plants. In contrast with this result, Mulder[38] found clearly lower pH-values of macerated root and shoot tissues of pea plants grown in nutrient solutions supplied with NH_4-N than in tissues of nitrate plants (see Table X). Similar results were obtained by Gouny[16] with maize and lupine plants.

TABLE X

Effect of the nitrogen compound and the pH of the culture solution on the pH of macerated leaf and root tissues of pea plants *)

N-compound added	Leaves and stems				Roots			
	pH=5.2	pH=6	pH=7	pH=7.6	pH=5.2	pH=6	pH=7	pH=7.6
No N added	5.65	5.87	6.00	6.06	5.52	5.58	5.72	5.87
KNO_3	6.14	6.17	6.32	6.28	5.78	5.88	5.98	6.18
$(NH_4)_2SO_4$	5.80	5.81	6.25	6.38	5.56	5.58	5.75	6.03
$(NH_4)_2HPO_4$	5.80	5.87	6.23	6.39	5.67	5.79	5.86	6.03

* For more detailed results see Ref. [38].

From the foregoing considerations it is concluded that the high concentration of NH_4- and H-ions at the root-cell surface and within the cytoplasm of root cells is the most plausible explanation of the occurrence of severe magnesium deficiency in plants growing in acid soils dressed with ammonium sulphate. That this effect is more pronounced, the higher the concentration of $(NH_4)_2SO_4$ added (Fig. 1), will be readily understood. Ions with a relatively high mobility like K will be less affected by this H-barrier than ions with a low mobility like Mg and Ca.

The beneficial effect of nitrate on uptake of cations, particularly of Ca- and Mg-ions, can be explained in a similar way. In the case of nitrate nutrition there may be assumed to occur a large excess of NO_3-ions in the outer layers of the root cells. Although nitrate nitrogen is less readily assimilated than ammonium nitrogen and therefore assimilation presumably will be extended over a greater number of cells, a certain proportion of the absorbed nitrate ions will also be assimilated in the cytoplasm of the root cells soon after their absorption. Assimilation of NO_3-ions which is a H-ion-consuming process takes place after exchange of NO_3- against HCO_3-ions. The presence of large amounts of the latter ions causes a binding of H-ions within the cytoplasm (see Table X) as well as at the root surface and in the medium surrounding the roots (see Ref. [44]). Since H-ions have to be considered as strongly competitive ions with respect to cations like Ca- and Mg-ions, the highly beneficial effect of nitrate ions on magnesium nutrition as observed in the present paper seems logical.

It may be asked if the explanation given of the observed phenomena fits in with the recently developed theories on ion absorption. From a number of investigations [1 8 9 10 24 30 46 59 63] it has become clear that metabolic processes are involved in the absorption of inorganic nutrients by plant cells. According to the Lundegårdh theory [8 9 10 30] the primary phase of absorption would be an adsorption at the cell surface, followed by an active, cytochrome-mediated, transport of anions through the cytoplasm. The cations would move non-metabolically through exchange against H-ions produced by dehydrogenase activity within the cell.

Other workers [12 46 47] have proposed the presence in the cytoplasm of metabolically generated carrier substances which combine with cations or anions, respectively, ($HR + M^+ \leftrightarrows MR + H^+$ (*1*), $ROH + A^- \leftrightarrows RA + OH^-$ (*2*)) and which are responsible for the transport of ions through at least part of the cytoplasm, through which the ions as such are unable to move.

Considering the Lundegårdh scheme the NH_4 (H)—Mg interaction could be seen mainly as an ion competition at the adsorbing surfaces of the cell. In addition the large amounts of H-ions resulting from the assimilation of NH_4-ions, undoubtedly would counteract the movement of Mg- and Ca-ions through the cytoplasm. The beneficial effect of nitrate can be explained by removing H-ions upon assimilation of the NO_3-ions.

In the case of the carrier theory the effect of the NH_4- (H-)-ions could be explained by assuming a promotion of the reversal of reaction (*1*) owing to the H-ions formed in the cytoplasm upon assimilation of NH_4-ions. Whether in addition NH_4 and Mg compete for a binding place on a specific carrier, as is assumed to occur with K and Rb [12], is as yet unknown.

SUMMARY

1. Wheat and oat plants were grown in acid soils, with and without added magnesium, at different levels of added nitrogen in the form of calcium or sodium nitrate, ammonium sulphate and ammonium nitrate (pot experiments). With increased rate of ammonium-sulphate addition the plants became increasingly deficient in magnesium. With sodium or calcium nitrate as the nitrogen source no magnesium deficiency occurred, while ammonium nitrate took an intermediate position. Similar results were obtained with wheat grown under field-experiment conditions.

2. In a pot experiment with wheat plants in which part of the roots were grown in a soil low in available magnesium and the other part in a sand-peat mixture free from magnesium, the beneficial effect of nitrate on magnesium nutrition was observed only when nitrate had been mixed with the soil, *i.e.* when magnesium and nitrate had to be taken up by the same roots.

3. The beneficial effect of nitrates, of calcium as well as of ammonium, on the magnesium nutrition of potato plants was found to be very pronounced. In a number of cases more severe symptoms of magnesium deficiency occurred in plants dressed with 80 kg of MgO per ha as $MgSO_4 \cdot H_2O$ in the absence of added nitrogen than in plants dressed with 140 kg of nitrogen in the form of ammonium nitrate limestone without added magnesium.

4. To elucidate the nitrogen—magnesium interactions, a comparison was made between direct effect (first year), after-effect (second year) and cumulative effect of the ammonium-sulphate and calcium-nitrate dressings, applied on a few experimental fields laid out on acid soils moderately poor in available magnesium. It was found that both the direct effect and the after-effect of an application of ammonium sulphate on the magnesium supply to crop plants were detrimental. Nitrate exerted its beneficial effect only in the year of application.

The unfavourable after-effect of ammonium-sulphate dressings on the magnesium nutrition was found to be due partly to a leaching of the available magnesium from the soil by the winter rains after the fall of soil pH. In addition the increased hydrogen-ion concentration in the soil may have an adverse effect on uptake of magnesium, either through a reduced development of the root system and a reduced functioning of the roots or through a decreased nitrification.

The detrimental direct effect of ammonium sulphate on the magnesium supply to the plants was assumed to be due to a competitive effect of NH_4- and H-ions on Mg-uptake. These ions are formed in great excess in the root tissues soon after the absorption of the NH_4-ions. Similarly the beneficial effect of nitrate on magnesium uptake was attributed to the decrease of H-ions within the cytoplasm after the assimilation of the nitrate by the root cells.

The results obtained in the present investigation were discussed in connection with recently developed theories on ion absorption.

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