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Results from experiments comparing aqueous and anhydrous ammonia with 'nitro-chalk' for grass cut for silage

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SUMMARY

In five experiments made at Rothamsted from 1966 to 1970 'Nitro-Chalk' (ammonium nitrate–calcium carbonate mixture, 21 % N) was broadcast for grass cut for silage, either in a single dose in spring or divided equally for three cuts. The 'Nitro-Chalk' was used to evaluate anhydrous ammonia (82 % N) in 1966, anhydrous ammonia and aqueous ammonia (approximately 26 % N) in 1967, 1968 and 1969, and anhydrous ammonia, aqueous ammonia and aqueous urea (18 % N) in 1970. All these fertilizers were applied to give 125, 250, 375 and 500 kg N/ha, except in 1968 when 250, 375, 500 and 625 kg N/ha were given.

Anhydrous ammonia gave smaller yields (of dry matter) than the other N fertilizers except in 1968, a wet year, when it was at least as good as 'Nitro-Chalk', but slightly less good than aqueous ammonia. Yields were larger with autumn- than with spring-injected aqueous ammonia and larger with either, than with equivalent single doses of 'Nitro-Chalk'. Yields with aqueous ammonia were also larger than with 'Nitro-Chalk' divided equally for three cuts when more than 375 kg N/ha was tested, but smaller with less. Aqueous urea was as good as a single dose of 'Nitro-Chalk' but less good than divided 'Nitro-Chalk' in 1970, the only year it was tested. 'Nitro-Chalk' divided equally for three cuts gave larger yields than when a single dose of up to 375 kg N/ha was given, but with more N than this a single dose was better.

Apparent recovery of N was least from anhydrous ammonia and differed little between autumn and spring injection in 1968, the only year when a valid comparison was possible. Apparent recoveries of N from autumn and from spring-injected aqueous ammonia and from 'Nitro-Chalk' broadcast in a single dose differed little, nor did the proportion of the N recovered at each cut. Recovery from 'Nitro-Chalk' broadcast in three equal amounts was more uniform, but little larger.

Judged by yield, no more than 375 kg N/ha was justified; grass given this amount of N either as aqueous ammonia or as 'Nitro-Chalk' removed approximately 29 kg of N, 3 kg of P (7 kg P_2O_5), 26 kg of K (31 kg K_2O) and 2 kg of Mg (3 kg MgO) per tonne of dry matter produced.

INTRODUCTION

Because grass has a longer growing season and needs more N to yield well than arable crops, it is likely to be the best crop on which to use a highly concentrated slowly acting N fertilizer such as anhydrous ammonia (82 % N). Ammonia needs no further processing before use, and, because it is the first product of N fixation, is the cheapest available source per unit of N. However, special equipment is needed to inject and to seal it both in arable soils and under grass. Earliest experiments with anhydrous ammonia in the U.K. were by Hunter & Jarvis (1953), who thought it unsuitable for grassland because of the power needed to pull the injection knives, and by Jameson (1959) who found that the smaller yields of grass with it than with solid N fertilizer could only partly be accounted for by sward damage during injection. Anhydrous ammonia was first introduced commercially in this country in 1965. In 1966 we began experiments to compare it with 'Nitro-Chalk' (mixture of calcium carbonate and ammonium nitrate, 21 % N) for spring wheat (Widdowson & Penny, 1970) and for grass cut for silage.

Aqueous ammonia (anhydrous ammonia dissolved in water, approximately 26 % N) was first sold to farmers in this country in 1963. It is easier to inject and to seal under grass than anhydrous ammonia, because it is a liquid under low pressure, instead of a gas liquefied under pressure, but Jameson (1959) found yields were little larger than from anhydrous ammonia when injected with the same machine. In 1966 we found it difficult both to measure accurately and to seal the anhydrous ammonia under the grass without loss. So in 1967 we included aqueous ammonia in the experiment and hired an applicator that had been specially adapted for trials work; this had no such problems. We used this applicator again in 1968, 1969 and 1970. (During 1969–71 we compared aqueous ammonia with 'Nitro-Chalk' for *grazed* grass and have published the results (Widdowson, Penny & Flint, 1972*a*).)

Because we had found that yields of barley grain were as large with injected aqueous urea (urea dissolved in water to give a solution containing 18 % N) as with injected aqueous ammonia, and larger with either than with broadcast 'Nitro-Chalk' (Widdowson, Penny & Flint, 1972*b*) we included aqueous urea in our 1970 experiment.

THE EXPERIMENTS

Treatments

Each experiment was at Rothamsted on a clay loam overlying 'Clay-with-Flints' using a 3-year ley in 1966, a long-term ley in 1969, but permanent grass otherwise. All except the 3-year ley had previously been given at least 175 kg N/ha annually for ensilage and grazing by cattle; they contained little clover. (Four fields were used; their names are below.)

West Barnfield I experiment, 1966

Anhydrous ammonia was injected in March into 3-year-old timothy–meadow fescue–white clover ley to supply 125, 250, 375 and 500 kg N/ha and compared with equivalent amounts of 'Nitro-Chalk' broadcast either all in March or one-third for each of three cuts. These 12 treatments, together with four plots not given N, were arranged in a randomized block design. Two of the plots not given N were 'cultivated' with the injector tines set at the same depth as on the plots given ammonia. There were four replicates.

Bones Close experiment, 1967

Anhydrous ammonia and aqueous ammonia were compared when injected into permanent grass to supply 125, 250, 375 and 500 kg N/ha either in November 1966 or in March. Yields from each were compared with those from equivalent amounts of 'Nitro-Chalk' broadcast either all in March or one-third in March, one-third after the first, and one-third after the second cut. These 24 treatments, together with two plots not given N, were arranged in a randomized block design. There were three replicates.

Parklands experiment, 1968

Permanent grass was used again. The design was the same as in 1967, but, to test the need for even larger amounts of N, we gave 250, 375, 500 and 625 kg N/ha instead of 125, 250, 375 and 500 kg N/ha.

Appletree experiment, 1969

A long-term grass ley was used. The treatments and the amounts of N tested were the same as in 1967.

Bones Close experiment, 1970

Anhydrous ammonia, aqueous ammonia and aqueous urea were each injected into permanent grass in spring to supply 125, 250, 375 and 500 kg N/ha and compared with equivalent amounts of 'Nitro-Chalk' broadcast either all in spring or one-third for each of three cuts. These 20 treatments, plus two plots not given N, were arranged in a randomized block design. There were four replicates.

A basal dressing of 1000 kg/ha of a fertilizer with 14 % P_2O_5 and 28 % K_2O was broadcast for each experiment.

Method

A rigid tool-bar fitted with disks and spring-loaded injection tines spaced 30 cm apart, each followed by a press wheel, was used to inject the anhydrous ammonia. The machine was calibrated on 'dummy' plots adjacent to each experiment. In 1966 and 1967 output was varied by regulating a valve and checked by weighing the ammonia tank before and again after injection. In 1966 the tank had to be removed for weighing, but in 1967 was weighed on a spring balance, suspended above it. When the appropriate setting had been determined for one amount, ammonia was then injected on appropriate plots and the tank re-weighed. This procedure was repeated for the other amounts. In 1968, 1969 and 1970 the anhydrous ammonia injector was fitted with a land-wheel-driven variable displacement pump and a rotameter so that the amount of liquid injected on each individual plot could be read off directly. The pump setting was determined for one amount by calibration and the appropriate plots injected; the pump then was reset and the procedure repeated for the remaining amounts. Appendix Table 1 shows that this new rig was much more accurate.

The required outputs from the aqueous ammonia and aqueous urea injectors (with injection knives 30 cm apart) were also determined by calibration

Table 1. *Dates of applying N fertilizers and of cutting grass in each experiment*

Year	Anhydrous ammonia injected: Autumn*	Anhydrous ammonia injected: Spring	Aqueous ammonia injected: Autumn*	Aqueous ammonia injected: Spring	Aqueous urea injected	'Nitro-Chalk' broadcast†	Cuts taken: 1	Cuts taken: 2	Cuts taken: 3
1966	—	2 Mar.	—	—	—	8 Mar.	17 May	4 July	5 Sept.
1967	15 Nov.	7 Mar.	7 Nov.	8 Mar.	—	22 Mar.	1 June	20 July	12 Oct.
1968	21 Nov.	14 Mar.	8 Nov.	12 Mar.	—	15 Mar.	22 May	9 July	14 Oct.
1969	14 Nov.	28 Mar.	13 Nov.	24 Mar.	—	24 Mar.	4 June	1 Aug.	15 Oct.
1970	—	10 Apr.‡	—	19 Mar.	20 Mar.	21 Mar.	3 June	4 Aug.	19 Oct.

* Autumn of previous year.

† Single dressings of 'Nitro-Chalk' and one-third of each divided dressing broadcast on these dates; one-third of divided dressings broadcast after first cut and again after second cut.

‡ 125 kg N/ha on 19 March.

adjacent to the experiments. We have already described (Widdowson, Penny & Flint, 1972*a*) how the commercial ammonia applicator was adapted for the experiments by fitting a burette to it. Appendix Table 1 shows that the amounts injected were close to those intended. The aqueous urea was injected with a similar applicator.

The 'Nitro-Chalk' was always broadcast by hand. In 1966 it was applied to supply the same amounts of N as anhydrous ammonia, but during 1967–70, when compared with more than one fertilizer, to supply exactly the intended amounts. Appendix Table 1 gives the intended amounts of N and the actual amounts supplied by each fertilizer in each experiment.

Individual plots were 2·1 m wide in 1966 and 2·4 m wide afterwards; they were 15·2 m long until 1969 when the growth of the grass in spring showed that the anhydrous ammonia injected the previous November had not properly filled the pipes for the first 5–7 m of the plot length. To prevent this happening in 1970 we doubled the length of the plots, injected them all in the same direction of travel and measured yields from the halves injected last.

We used seven tines 30 cm apart (total width of 2·1 m) in 1966 but either six, seven or eight tines (1·8, 2·1 or 2·4 m) afterwards, the number varying with the machine and surface conditions. At harvest we discarded a small area at each end of each plot (half of each plot in 1970) and then cut and collected a central swath 1·5 m wide with an experimental grass harvester (Chalmers & Kemp, 1962). After weighing the grass, samples were taken from each plot to determine % dry matter and % N each year and % P and % K from 1967 onwards; % Mg in grass grown with spring-applied aqueous ammonia and 'Nitro-Chalk' was also determined each year during 1967–70. Table 1 shows when the fertilizers were applied, and when the grass was cut each year.

Field observations

West Barnfield I experiment, 1966

The anhydrous ammonia could be injected only 6–8 cm deep and much escaped from the badly sealed slits, especially with the two larger amounts. By 12 April, 'Nitro-Chalk' was giving good growth, but anhydrous ammonia little; the injection slits and the scorched grass along their edges were still obvious. Some of the injection slits were still showing at the second cut (4 July).

Bones Close experiment, 1967

Both anhydrous and aqueous ammonia were injected 10–12 cm deep, both in autumn and in spring, with little loss. On 31 March the grass was seen to be scorched by 'Nitro-Chalk' supplying 375 or 500 kg N/ha, whereas that injected with either form of ammonia in autumn was growing well. By 17 April, the autumn injection slits were still just visible but the spring ones were very obvious; the tallest grass (20–22 cm) was given by 500 kg N/ha of aqueous ammonia injected in autumn. By 4 July the spring injection slits had opened during the dry weather and the grass near them was brown.

Parklands experiment, 1968

Both anhydrous and aqueous ammonia were injected 10–12 cm deep. The soil was very wet in autumn and some tractor wheel-slip damaged the sward. In spring, although the surface was dry, the soil was wet underneath and wheel-slip was still troublesome during injecting. On 29 March it was seen that the grass was scorched by 'Nitro-Chalk' supplying either 500 or 625 kg N/ha, and a little, along the slits, by spring-injected anhydrous ammonia supplying 625 kg N/ha; grass was responding to both forms of ammonia injected in autumn. By 26 April the best growth at each amount of N was from single dressing of 'Nitro-Chalk'.

Appletree experiment, 1969

Anhydrous ammonia was injected 11–13 cm deep and the sward was slightly damaged by tractor wheel-slip in autumn. Aqueous ammonia was injected about 10 cm deep. By 17 April the grass was just beginning to grow but was scorched by 375 and 500 kg N/ha as 'Nitro-Chalk'; injection slits made in spring opened up during a dry spell at this time. By 23 April the best growth was from autumn-injected aqueous ammonia; grass given 500 kg N/ha as 'Nitro-Chalk' was still scorched. On 30 June ($3\frac{1}{2}$ weeks after first cut) it was seen that injection slits made in spring had again opened in dry weather.

Bones Close experiment, 1970

All injections were made 10–12 cm deep. By 5 May the best grass (from 'Nitro-Chalk') was about 25 cm tall; growth of grass given 500 kg N/ha as 'Nitro-Chalk' was still slightly checked, and injection slits from anhydrous ammonia tines had opened. By 21 May the best grass lodged, though only 38–45 cm tall; growth from aqueous urea was better than from aqueous ammonia and as good as from single dressings of 'Nitro-Chalk'. On 8 September visual scores showed that growth from aqueous urea was better than from aqueous ammonia and better from either than from single dressings of 'Nitro-Chalk', but not from divided dressings of it.

RESULTS

Yields

Appendix Table 2 shows yields from each cut in each experiment, without N and with each amount of each N fertilizer tested. The commonest method of applying N for intensively used grass is to broadcast granular fertilizer for each cut, so Table 2 first shows the total annual yields in each experiment from 'Nitro-Chalk' broadcast in equal amounts for the three cuts and then uses each as the standard ($\equiv 100$). The total yields from the other N fertilizers have been expressed as percentages of the yield given by this standard treatment, at each amount of N.

West Barnfield I experiment, 1966

Yields without N (Appendix Table 2) are from plots which had the injector tines pulled through them; they differed insignificantly from yields from the undisturbed sward and were very small at the first and second cuts and negligible at the third. At the first cut, yields with anhydrous ammonia were only half to two-thirds of those with equivalent amounts of 'Nitro-Chalk'; the most ammonia (500 kg N/ha) gave less grass (3·14 t/ha) than the least 'Nitro-Chalk' (125 kg N/ha) did (4·46 t/ha).

At the second cut, anhydrous ammonia again gave less grass than the single dressing of 'Nitro-Chalk', but divided dressings of 'Nitro-Chalk' (two-thirds applied) now gave more grass than the single dressings. Yields from anhydrous ammonia and the single dressings of 'Nitro-Chalk' were smaller than at the first cut, but larger with the divided dressings of 'Nitro-Chalk'.

At the third cut, anhydrous ammonia did not increase yields whereas the two larger amounts of spring-applied 'Nitro-Chalk' did, though they in turn were less effective than the divided dressings, which gave up to 3·44 t/ha.

Averaging amounts of N, anhydrous ammonia gave 51 % of its total yield at the first cut, 45 % at the second and only 4 % at the third, with corresponding values from 'Nitro-Chalk' applied in one dose, of 49, 42 and 9 %, so anhydrous ammonia was no more persistent than 'Nitro-Chalk'. The distribution of yield with 'Nitro-Chalk' broadcast in equal amounts for each cut was much better, it gave 35, 40 and 25 % of total yield at the first, second and third cuts respectively.

Table 2 shows that total yields with spring-applied 'Nitro-Chalk' ranged from 78 to 92 %, but with anhydrous ammonia only from 46 to 57 %, of that given by an equivalent amount of 'Nitro-Chalk' broadcast for each cut. The small yields with anhydrous ammonia may partly be explained by losses from too shallow injection.

Bones Close experiment, 1967

Appendix Table 2 shows that this permanent grass yielded as much at the first cut without N (4·67 t/ha) as the ley did in 1966 when given optimum N; there was little benefit in giving this previously grazed grass more than 250 kg N/ha. Our failure to apply the correct amounts of anhydrous ammonia (with one exception, we applied much more than intended) precludes its comparison with equivalent amounts of the other fertilizers, e.g. the large yield shown from 125 kg N/ha applied in spring was in fact from almost double the amount of N (Appendix Table 1). Autumn-applied aqueous ammonia gave more grass than either spring-applied aqueous ammonia (maximum difference, 1·01 t/ha) or spring-applied 'Nitro-Chalk' (maximum difference, 0·92 t/ha). There was no benefit from giving more than 83 kg N/ha as 'Nitro-Chalk' for this first cut.

Typically, the grass grew much less during the second and third cutting periods (June–September was drier than average) than during the first, but even so, the best N treatment increased yields from 0·79 to 3·22 t/ha at the second cut and from a negligible 0·29 to 2·86 t/ha at the third. Autumn-

Table 2. *Total yields (t/ha) of dry grass each year, from 'Nitro-Chalk' broadcast in equal amounts for each of three cuts* (≡ 100 %) *and the relative yields (as a %) from equivalent amounts of 'Nitro-Chalk' broadcast as a single dressing in spring, and from several liquid N fertilizers injected either in autumn or in spring at Rothamsted*, 1966–70

N applied (kg/ha)*	Yields from 'Nitro-Chalk' broadcast in three equal amounts	Yields as a percentage of that from an *equivalent* amount of 'Nitro-Chalk' broadcast in three equal amounts: 'Nitro-Chalk' broadcast in spring	Anhydrous ammonia injected: In autumn	Anhydrous ammonia injected: In spring	Aqueous ammonia injected: In autumn	Aqueous ammonia injected: In spring	Aqueous urea injected in spring
	West Barnfield I experiment, 1966						
125	7·89 (≡ 100)	92	—	57	—	—	—
250	11·97 (≡ 100)	78	—	48	—	—	—
375	12·60 (≡ 100)	81	—	46	—	—	—
500	12·65 (≡ 100)	86	—	49	—	—	—
	Bones Close experiment, 1967						
125	8·77 (≡ 100)	95	83	101	95	88	—
250	11·68 (≡ 100)	74	69	80	88	78	—
375	11·71 (≡ 100)	84	83	86	96	91	—
500	12·15 (≡ 100)	100	84	84	103	98	—
	Parklands experiment, 1968						
250	9·88 (≡ 100)	99	103	109	108	106	—
375	10·08 (≡ 100)	103	104	102	106	109	—
500	9·80 (≡ 100)	106	106	106	114	108	—
625	10·01 (≡ 100)	101	103	104	108	102	—
	Appletree experiment, 1969						
125	8·24 (≡ 100)	88	57	87	89	92	—
250	10·17 (≡ 100)	88	54	74	81	86	—
375	10·43 (≡ 100)	90	70	78	93	93	—
500	9·73 (≡ 100)	100	86	95	100	103	—
	Bones Close experiment, 1970						
125	8·08 (≡ 100)	92	—	85	—	89	85
250	9·58 (≡ 100)	87	—	81	—	86	92
375	9·65 (≡ 100)	94	—	92	—	93	95
500	9·59 (≡ 100)	91	—	90	—	104	91

NOTE: data to be compared horizontally only.
* Intended amounts of N, actual amounts applied are in Appendix Table 1.

and spring-injected aqueous ammonia and single dressings of 'Nitro-Chalk' then all gave similar yields, which were smaller than with 'Nitro-Chalk' broadcast in three equal amounts, except when 500 kg N/ha was given. Then, a single dose of N (in either form) gave the larger yield at the second cutting, though only spring-applied aqueous ammonia yielded as much at the third cutting. Evidently a very large amount of N, even as aqueous ammonia, is needed to give as good a distribution of yield as 'Nitro-Chalk' applied in equal amounts for each cut.

Averaging amounts of N, 65 % of the total yield given by autumn-injected aqueous ammonia came from the first cut, 23 % from the second and only 12 % from the third; the corresponding values for spring-applied aqueous ammonia were 61, 25 and 14 % and for spring-applied 'Nitro-Chalk' 63, 25 and 12 %, all very similar. With 'Nitro-Chalk' broadcast for each cut, less of the total yield (55 %) came from the first cut, and more (20 %) from the third.

Table 2 shows that total yields with a single dose of 'Nitro-Chalk' and with aqueous ammonia were smaller than with 'Nitro-Chalk' broadcast equally for three cuts until 500 kg N/ha was given; then they were similar. Although we applied more N as anhydrous ammonia than intended (Appendix Table 1) Table 2 shows that the yields from it equalled those from divided dressings of 'Nitro-Chalk' in only one, and those from aqueous ammonia in only two, of eight comparisons.

Parklands experiment, 1968

The anhydrous ammonia was applied much more accurately than in 1967 because it was metered instead of weighed, and yields from it may be compared with those from other fertilizers. At the first cut, yield without N was 2·66 t/ha (Appendix Table 2) and again there was little benefit from giving more than 83 kg N/ha as 'Nitro-Chalk'. Yields with the two kinds of ammonia differed little (maximum 4·58 t/ha with anhydrous and 4·81 t/ha with aqueous); both gave slightly more grass when injected in autumn than in spring. 'Nitro-Chalk' broadcast in one dose in spring was consistently less good than either sort of ammonia injected the previous autumn and slightly less good than 'Nitro-Chalk' supplying one-third as much N (in three of the four comparisons).

At the second cut, grass not given N yielded 2·28 t/ha and, although maximum yield always came from applying more than 250 kg N/ha, the extra yield was small. Yields from the two ammonia treatments differed little and were similar to those with a single dressing of 'Nitro-Chalk'.

At the third cut, grass not given N yielded more (2·95 t/ha) than at either the first or second cuts, and, unusually, N mostly decreased yields. 'Nitro-Chalk' broadcast equally for three cuts decreased them most. The small responses to more than 250 kg N/ha at the first and second cuts may be explained by the N content of this soil (judged by % N in grass not given N, Appendix Table 3) and the decreases in yield at the third cut by the dull, wet autumn. From April to September there were 247 h less sunshine than average, and of this deficit 164 h occurred after 1 July. Rainfall from 1 April to 30 September exceeded the average by 115 mm, and of this excess 99 mm fell after 1 July.

Distribution of total yield was similar with each method of applying N and ranged from 39 to 43 % at the first cut, from 31 to 34 % at the second and from 25 to 27 % at the third, so in this wet year growth was no more uniform with divided than with single doses of N.

Table 2 shows that, in contrast to the previous 2 years, total yields from broadcasting the 'Nitro-Chalk' in three equal amounts were smaller than from broadcasting it in one dose, which in turn was slightly less good than injecting the N as either form of ammonia. Total yields from aqueous ammonia were marginally larger than from anhydrous ammonia when injected in autumn, but no different when injected in spring.

Appletree experiment, 1969

Because of faulty application (see Methods), yields with anhydrous ammonia injected in autumn were not included in the statistical analyses and cannot properly be compared with other yields.

Appendix Table 2 shows that at the first cut the yield without N was 2·49 t/ha, but although N doubled yield there was little benefit from giving more than 125 kg N/ha. Yields from aqueous ammonia were slightly larger when it was injected in autumn than in spring, and larger than from anhydrous ammonia injected in spring, or from single dressings of 'Nitro-Chalk'. 'Nitro-Chalk' supplying 375 or 500 kg N/ha scorched the grass and decreased yields, whereas the large doses of ammonia were harmless.

At the second cut the yield without N declined to 1·37 t/ha. The grass responded up to 500 kg N/ha as spring-injected anhydrous ammonia (3·83 t/ha), but only three-quarters as much N as spring-applied aqueous ammonia or 'Nitro-Chalk' was needed to give the same yield. Aqueous ammonia now gave a slightly larger yield when injected in spring than in autumn, but 'Nitro-Chalk' broadcast in equal amounts (two-thirds as much N) gave larger yields, except when 500 kg N/ha was given.

At the third cut the yield without N (0·18 t/ha) was the smallest recorded in the five experiments. The maximum yield with anhydrous ammonia was only 0·72 t/ha and with aqueous ammonia 1·19 t/ha. Yields with 'Nitro-Chalk' applied in three equal doses always exceeded 1 t/ha, but the maximum was only 1·54 t/ha. These small yields may be explained by the weather, rainfall being 76 mm less and sunshine 106 h less than average, from 1 August to 30 September.

Nitrogen applied in a single dose (averaging amounts and ignoring autumn-applied anhydrous ammonia) gave from 54 to 58 % of total yield at the first cut, from 34 to 38 % at the second and only from 5 to 7 % at the third. Corresponding values for 'Nitro-Chalk' broadcast for each cut were 50, 36 and 14 %, so divided dressings did little to even out growth.

Table 2 shows that total yields from a single dose of 'Nitro-Chalk' and from aqueous ammonia were smaller than from 'Nitro-Chalk' broadcast in three equal amounts until 500 kg N/ha was given. Anhydrous ammonia injected in spring also gave smaller yields than divided dressings of 'Nitro-Chalk', but again compared best with it (95 % as good) when 500 kg N/ha was given.

Bones Close experiment, 1970

The anhydrous ammonia injector was unsatisfactory at first and had to be repaired. Consequently the anhydrous ammonia was applied three weeks later than the other fertilizers, so yields with it were not statistically analysed with the others. Appendix Table 2 shows that at the first cut yield without N was large (4·60 t/ha) and almost identical to that on the same field in 1967, but the response to N was smaller; with each fertilizer, 125 kg N/ha was enough for maximum yield. Yields with aqueous ammonia were larger than with equivalent amounts of either aqueous urea or 'Nitro-Chalk' and yields with each were larger than with anhydrous ammonia (injected 3 weeks later). The largest dressings of 'Nitro-Chalk' again decreased yields.

At the second cut, yield without N was only 0·39 t/ha. Although the grass responded to at least 375 kg N/ha, the best yield was only 1·56 t/ha (with 'Nitro-Chalk'), perhaps because rainfall during June and July was only 72 mm (44 mm less than average). Differences between the fertilizers were inconsistent, but 'Nitro-Chalk' broadcast on the surface was as effective as injected N during this dry weather.

At the third cut, yield without N was a negligible 0·27 t/ha, but yields with N were larger than at the second cut, the only experiment of the five where this happened, perhaps because 115 mm of rain fell in August and September, only 11 mm less than average. Aqueous ammonia gave smaller yields than equivalent amounts of other sorts of N until 500 kg N/ha was given, then it gave more. Yields with aqueous urea and with anhydrous ammonia were similar, and slightly larger than with a single dose of 'Nitro-Chalk', but smaller than with 'Nitro-Chalk' broadcast in three equal amounts.

Distribution of total yield differed little between fertilizers; 63–67% was produced at the first cut, 14–15% at the second, but 19–23% at the third.

Table 2 shows that 'Nitro-Chalk' broadcast for each cut gave the largest yield, except when 500 kg N/ha was given; then aqueous ammonia was best; its yields ranged from 86–104% of those from divided dressings of 'Nitro-Chalk'. The relative value of 'Nitro-Chalk' broadcast in a single dose ranged from 87 to 94%, of anhydrous ammonia (injected later in spring) from 81 to 92%, and of aqueous urea from 85 to 95%, of the standard divided dressings.

Table 3. *Total annual yields (t/ha) of dry grass from injecting aqueous ammonia either in autumn or in spring and from broadcasting 'Nitro-Chalk', either in one dose in spring or in equal doses for each of three cuts*

Yields are means of 3 years, 1967–9.

	Aqueous ammonia injected		'Nitro-Chalk' broadcast	
N applied (kg/ha)	In autumn	In spring	All in spring	One-third per cut
250	9·72	9·45	9·14	10·58
375	10·53	10·44	9·86	10·74
500	11·14	10·86	10·76	10·56
Mean	10·46	10·25	9·92	10·63

Aqueous ammonia versus 'Nitro-Chalk'

Table 3 compares total annual yields with aqueous ammonia and with 'Nitro-Chalk' at the three amounts of N common to the 1967, 1968 and 1969 experiments. With 250 or 375 kg N/ha, the largest yields (10·58 and 10·74 t/ha) came from broadcasting 'Nitro-Chalk' in equal amounts for the three cuts and the smallest (9·14 and 9·86 t/ha) from broadcasting it in a single dose in spring; yields with aqueous ammonia were intermediate and were slightly larger with it injected in autumn than in spring. With 500 kg N/ha, however, broadcasting 'Nitro-Chalk' in three equal amounts decreased yields slightly (10·56 t/ha) and then injecting aqueous ammonia in autumn gave the largest yield (11·14 t/ha). Injecting aqueous ammonia in spring consistently gave yields slightly larger than broadcasting 'Nitro-Chalk' in spring,

Table 4. *Total yields (t/ha) of dry grass from three cuts taken from 'uncultivated' swards and from those 'cultivated' either with the anhydrous or with the aqueous ammonia injector*

Yields averaged over three amounts of N (42, 83 and 125 kg N ha/cut all given as 'Nitro-Chalk').

		'Cultivation'				
		With anhydrous ammonia injector		With aqueous ammonia injector		
Year	None	In autumn	In spring	In autumn	In spring	S.E.
1967	10·76 (±0·200)	11·07	10·67	11·21	10·35	±0·282
1968	10·20 (±0·410)	9·88	10·03	10·44	11·03	±0·580
Mean	10·48	10·48	10·35	10·82	10·69	—

presumably because it leached less and did not scorch the leaves. So, if the farming system justifies using 375 kg N/ha or more, this may conveniently be injected in autumn or in spring as a single dose of aqueous ammonia, with little or no loss of yield or efficiency relative to broadcast dressings of 'Nitro-Chalk' repeated through the year.

Effects of slits made by injectors

In 1967 and 1968 we measured in subsidiary experiments (adjacent to the main ones) the effects of the ammonia injectors on yield. 'Nitro-Chalk' was broadcast to give 42, 84 or 125 kg N/ha per cut on undisturbed plots and on plots 'cultivated' either in autumn or in spring, with either the anhydrous or the aqueous ammonia injector. The 18 treatments were arranged in a single replicate. Table 4 shows that yields were not significantly changed by pulling the injectors through the sward, but the contrasting effects in the two years reflected contrasting soil conditions. Slits were made under good conditions both in autumn 1966 and in spring 1967. Slits made in autumn contracted during winter and expanded less during dry weather in summer than slits made in spring; yields were larger with autumn than with spring 'cultivation'. The soil was very wet in autumn 1967 and wheel-slip was more troublesome than in spring 1968; yields were smaller with autumn than with spring 'cultivation'. The broader tines used to inject the anhydrous ammonia damaged the sward more; yields were smaller.

N content of grass

Appendix Table 3 shows the mean percentages of N in three cuts of dry grass, the total amounts (kg/ha) taken up in the three cuts and the apparent percentage recoveries of fertilizer N by the grass each year.

West Barnfield I experiment, 1966

Without fertilizer N, the % N in the herbage (1·64) was less than in any of the following experiments even though this ley contained some white clover, so this arable soil supplied less N (49 kg/ha) than the grassland soils used afterwards (three under permanent grass, one under a long ley). With anhydrous ammonia, % N ranged from 1·68 to only 2·13, but with 'Nitro-Chalk' from 1·83 to 3·12; it differed little between 'Nitro-Chalk' broadcast in spring and equally for the three cuts. With 500 kg N/ha given as anhydrous ammonia the grass removed only 127 kg N/ha, no more than grass given only 125 kg N/ha broadcast as 'Nitro-Chalk' in spring. Grass given equal amounts of 'Nitro-Chalk' for each cut removed slightly more N (maximum 383 kg/ha) than grass given it all in spring (maximum 369 kg/ha). The grass apparently recovered only from 13 to 20 % of the N in anhydrous ammonia, from 51 to 69 % of the N in a single dose of 'Nitro-Chalk' and from 64 to 73 % of the N in 'Nitro-Chalk' broadcast in three equal amounts. So, judged by % N, uptake of N and recovery of N, anhydrous ammonia was much less efficient than 'Nitro-Chalk'.

Bones Close experiment, 1967

Without N, the herbage contained 2·0 % of N and removed 103 kg N/ha. Although we applied much more anhydrous ammonia than intended, both the % N in the herbage given it and the recovery of the N by the grass were usually smaller than from aqueous ammonia, which behaved very much like the single dressings of 'Nitro-Chalk'. There was little difference between the efficiency of autumn- and spring-applied aqueous ammonia (maximum % N, 3·08, maximum uptake of N, 379 kg/ha), but the largest uptake (438 kg N/ha) and recovery (67 %) of N was by grass given 500 kg N/ha as 'Nitro-Chalk' in spring. 'Nitro-Chalk' applied for each cut was less efficient than a single dose of 'Nitro-Chalk', or of aqueous ammonia, in direct contrast to our results on the arable soil in 1966. The grass apparently recovered only from 20 to 60 % of the N in anhydrous ammonia, but from 53 to 70 % of the N in aqueous ammonia and from 44 to 69 % of the N in 'Nitro-Chalk'. So, anhydrous ammonia was less efficient than aqueous ammonia and again less efficient than 'Nitro-Chalk' whether judged by % N, uptake of N, or recovery of N.

Parklands experiment, 1968

Without N, both % N in dry grass and uptake of N (170 kg N/ha) were larger than in any of the other experiments, so this soil was by far the richest in N. Both % N and N uptake were larger in grass grown with aqueous than with anhydrous ammonia and values for each differed little between autumn and spring injections. The recoveries of N by grass grown with aqueous ammonia and with a single dose of 'Nitro-Chalk' were similar, but grass given one third of its N for each cut recovered less than either (both as % and as uptake). Percentage recoveries of N were less than in 1966 or 1967, most probably because the grass responded less in the dull wet summer. They ranged from 28 to 41 % with anhydrous ammonia, 32 to 50 % with aqueous ammonia, 32 to 47 % with 'Nitro-Chalk' in a single dose, and from 28 to 34 % with 'Nitro-Chalk' applied in three equal doses. Judged by % N in grass, uptake and recovery of N, aqueous ammonia and spring-applied 'Nitro-Chalk' were again more efficient than anhydrous ammonia, but unusually 'Nitro-Chalk' applied in three equal doses was not.

Appletree experiment, 1969

Without N, the herbage from this long ley contained 1·71 % N and removed 65·4 kg N/ha, only slightly more than the short ley did in 1966. Less N was recovered from anhydrous ammonia injected in autumn than from any other treatment (presumably because the applicator did not work properly). Except with 125 kg N, grass given aqueous ammonia in spring contained more N and recovered more of that given than grass given anhydrous ammonia in spring, though no more than from a single dressing of 'Nitro-Chalk'. Also, aqueous ammonia was as effective when injected in autumn as in spring, when judged in either way; the recovery of it ranged from 67 % of 125 kg N/ha to 44 % of 500 kg N/ha. More N was recovered from three equal amounts of 'Nitro-Chalk' than from a single dose, except when 500 kg N/ha was tested, and the recovery of these divided dressings ranged from 69 % of the smallest to 40 % of the largest.

Bones Close experiment, 1970

Without N, the herbage contained 1·97 % N and removed 92 kg N/ha, only a little less than in 1967. With N, % N differed little between fertilizers and ranged from 2·31 with 125 kg N/ha to 3·28 with 500 kg N/ha. Grass took up slightly, but consistently more N from aqueous urea than from anhydrous ammonia and again slightly more than from aqueous ammonia or 'Nitro-Chalk' until 500 kg N/ha was given, then it was not quite as efficient. So, judged by uptake, urea injected like this was as efficient as the other fertilizers, in direct contrast to its smaller value when surface applied (Cooke, 1964). The very large recovery (96 %) from the smallest amount of anhydrous ammonia is suspect, because although the meter showed that we had applied only 86 kg N/ha (Appendix Table 1), we later found that the pump was not working properly.

The recovery of N from aqueous ammonia and 'Nitro-Chalk'

Table 5 shows % N, removal (kg/ha) and % recovery of N, averaged over the three experiments in which aqueous ammonia was injected both in autumn and in spring. At the first cut, % N was largest with a single spring dressing of 'Nitro-Chalk', and larger with aqueous ammonia injected in spring than in autumn, but at the second and third cuts differed little. The % N in grass given equal amounts of 'Nitro-Chalk' for each cut was smaller at the first cut, but larger at the second and

Table 5. *The percentage of N in, and the amount of N removed by, each of three cuts of grass grown without N fertilizer and with either aqueous ammonia or 'Nitro-Chalk', and the apparent percentage recoveries of N from these two fertilizers*

Mean of 3 years, 1967–9.

	Percentage of N in dry grass			Amounts (kg/ha) of N recovered			Percentage of total amount of fertilizer-N apparently recovered in			
Cut...	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	Total of 3 cuts
N applied (kg/ha)										
None	1·80	1·84	2·20	58·4	26·6	27·9	—	—	—	—
As aqueous ammonia injected in autumn										
250	2·79	2·23	2·18	145·1	68·7	32·2	34	16	2	52
375	3·05	2·77	2·64	167·2	90·5	46·3	28	17	5	50
500	3·23	3·03	3·09	179·5	101·1	70·2	23	14	8	46
As aqueous ammonia injected in spring										
250	2·90	2·28	2·28	146·8	68·3	34·1	35	16	2	54
375	3·19	2·70	2·43	164·6	92·6	44·5	28	18	4	50
500	3·45	3·17	2·96	176·8	107·8	69·8	23	16	8	47
As 'Nitro-Chalk' broadcast in spring										
250	3·11	2·22	2·31	149·7	66·2	31·2	36	16	1	53
375	3·37	2·67	2·67	161·7	88·5	45·1	27	16	5	48
500	3·86	3·17	3·03	197·3	113·1	63·3	28	17	7	52
As 'Nitro-Chalk' broadcast in three equal amounts (one per cut)*										
250	2·36	2·40	2·54	123·8	78·3	52·3	78	62	29	56
375	2·22	3·02	3·12	112·9	104·3	68·5	43	62	33	46
500	2·65	3·12	3·09	137·2	100·2	63·7	47	44	21	38

* Apparent recoveries from 'Nitro-Chalk' broadcast in three equal amounts calculated as % of that given for each cut.

Table 6. *The percentages of P, K and Mg (in dry grass) at each of three cuts and the total amounts removed by grass given either aqueous ammonia or 'Nitro-Chalk' in spring*

Means of 4 years, 1967–70.

	%P			%K			%Mg			Total amounts (kg/ha) removed		
Cut...	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	P	K	Mg
N applied kg/ha												
As aqueous ammonia in spring												
250	0·31	0·26	0·29	3·06	2·56	2·19	0·16	0·17	0·21	26·9	254·0	15·3
375	0·32	0·25	0·27	2·99	2·31	2·17	0·16	0·20	0·20	29·4	265·0	17·9
500	0·32	0·26	0·26	3·14	2·50	1·93	0·16	0·20	0·23	30·9	282·8	19·4
As 'Nitro-Chalk' in spring												
250	0·33	0·25	0·29	3·08	2·45	2·14	0·17	0·18	0·20	27·0	243·1	15·4
375	0·33	0·24	0·27	3·13	2·47	2·20	0·17	0·19	0·19	28·2	265·4	17·0
500	0·34	0·25	0·25	3·12	2·40	2·20	0·16	0·20	0·22	30·2	277·3	18·2

third cuts than in grass given spring dressings of N, except when 500 kg N/ha was given. N in grass was increased by giving N fertilizer from 1·80 to 3·86 % N in dry matter at the first cut, from 1·84 to 3·17 at the second, and from 2·20 to 3·12 at the third.

Table 5 also shows how similar were the amounts of N removed by grass given aqueous ammonia, either in autumn or in spring and from aqueous ammonia at either time and the single dose of 'Nitro-Chalk'. The largest difference was only about 20 kg N/ha and that in grass given 500 kg N/ha as 'Nitro-Chalk' for the first cut.

Table 5 also shows that the apparent percentage recovery of N from fertilizer by individual cuts was similar from equivalent amounts of aqueous ammonia and 'Nitro-Chalk' (single dose) and that two-thirds of the recovery from 250 kg N/ha and half of the recovery from 500 kg N/ha was at the first cut. Recovery from 'Nitro-Chalk' applied in three equal doses was slightly more uniform. The apparent recovery of the applied N in all three cuts ranged from 46 to 54 % with aqueous ammonia, 48 to 53 % with 'Nitro-Chalk' in a single dose and 38 to 56 % with 'Nitro-Chalk' in three equal doses. So the smallest and the largest recovery was from the divided dressings of N.

P, K and Mg contents

From 1967 to 1970 % Mg was determined in the dry grass to see if it differed when N was given in spring wholly (aqueous ammonia) rather than partly ('Nitro-Chalk') in the ammonium form. Table 6 shows that it did not, but that it was smallest (about 0·16 %) at the first and largest (about 0·21 %) at the third cut, and tended to increase slightly with increasing amounts of N at the second and third cuts, but not at the first. Amounts (kg/ha) of Mg removed by the three cuts ranged from 15·3 with 250 kg N/ha to 19·4 with 500 kg N/ha.

Table 6 also shows that % P and % K in the grass differed little with either form or amount of N. Percentage P was slightly larger (about 0·32 %) at the first than at the second or third cuts. Percentage K was also largest (about 3·1 %) at the first cut and smallest (about 2·1 %) at the third cut, in direct contrast to % Mg. The table also shows that amounts of P and K removed in three cuts differed little between aqueous ammonia and 'Nitro-Chalk' and ranged from about 27 kg P and 250 kg K/ha when 250 kg N/ha was given, to about 30 kg P and 280 kg K/ha when 500 kg N/ha was given.

DISCUSSION

Since we started our experiments several authors have reported work with anhydrous ammonia, but few with aqueous ammonia for grassland. Most experiments showed that anhydrous ammonia gave smaller yields of grass than solid N fertilizers. Typical results were presented at a Symposium at the National College of Agricultural Engineering, Silsoe, Bedford, in 1970. Whitear reported experiments by Fisons Ltd., showing that anhydrous ammonia was only 30–95 % as good as ammonium nitrate, as ammonium sulphate or as ammonium sulphate nitrate, for increasing yields of dry matter and N uptake. He stated that some of the inefficiency may have been due to loss of gas at injection, to the decomposition of ammonium nitrite if formed at the point of injection and by damage to the sward on heavy soils. At the same Symposium, Herriott *et al.* showed that, in the east of Scotland, anhydrous ammonia produced 78–97 % as much dry matter as solid N fertilizer; the injection knives often severely damaged the short-term leys common there, but not old swards. In our experiments ammonia gas escaped during injection very obviously in 1966, and though little escaped in later years, some scorch showed later, along the slits. In subsidiary experiments (Table 4) the anhydrous ammonia injector damaged the sward enough to decrease yields (non-significantly) in three of four comparisons.

Reid & Castle (1970) found that in south-west Scotland single applications of anhydrous ammonia gave less yield than ammonium nitrate repeatedly broadcast during the growing season. Because they minimized ammonia loss and sward damage by using a hand injector, they suggested that anhydrous ammonia was inferior because of the slower uptake of N from it, particularly in spring, and that uptake might be improved by winter or early spring injection. We compared autumn and spring applied anhydrous ammonia for 3 years, but accurately only in 1968 when they were equally effective. Aqueous ammonia was applied accurately in all 3 years and total yields were similar with autumn and with spring injection in each. Yields at the first cut usually were larger with the autumn applications than with the spring, though the amounts of N recovered were not. So, the larger yields with autumn injection were most probably because nitrification and N uptake in spring were earlier, which would support Reid & Castle's suggestion.

Gasser, Blakemore & Flint (1972) used a small hand-injector to apply anhydrous ammonia in several injection patterns (rows and square or nearly square spacing) and concluded that, although injection in rows was the most efficient method of application, the consequence of concentrating the ammonia in bands 30 cm apart (the usual spacing) was direct damage to the grass along the lines of injection, thus diminishing yield. Large amounts of anhydrous ammonia (500 kg N/ha) scorched the grass along the slits in our experiments, but equivalent amounts of 'Nitro-Chalk' scorched more grass more uniformly, so the expansion of the injection slits during dry weather and the consequent drying, may have decreased yield as much as scorch did.

The inefficiency of anhydrous ammonia in our experiments therefore seems to have been due to a combination of (1) loss of gas during injection, (2) scorching of the grass along the lines of injection, (3) mechanical damage by the injector tines, (4) loss of moisture along the injection slits during dry weather, and (5) a slower and smaller recovery of N.

Exceptionally, Williams & Cooke (1972) found anhydrous ammonia to be as efficient as 'Nitro-Chalk' for grass on the sandy clay soil at Saxmundham, Suffolk. This was undoubtedly because much of the nitrate N from the 'Nitro-Chalk' was leached by heavy and at times intense rain, which fell shortly after they had both been applied in March 1969 (Williams, 1971). Leaching of nitrate-N may partly explain why anhydrous ammonia was at least as good as 'Nitro-Chalk' in our 1968 experiment; but even then it was still slightly less good than aqueous ammonia. Whitear (1970) also found that anhydrous ammonia compared best with solid N fertilizer when rainfall was either well distributed or above average, underlining the risks of losing nitrate-N by leaching in spring.

There are fewer published results of experiments with aqueous ammonia to compare with ours. Cowling (1968) found single applications of aqueous ammonia as good as single dressings of ammonium nitrate, but not as good as divided dressings for ryegrass, agreeing broadly with our results. Hodgson & Draycott (1968) concluded that aqueous ammonia was as effective as ammonium sulphate or as a solution of ammonium nitrate and urea for grass. There were several reasons why aqueous ammonia was a better N fertilizer for grass than anhydrous ammonia in our experiments. We found (1) that aqueous ammonia was easier to inject satisfactorily into our 'Clay-with-Flints' soil than anhydrous ammonia and the absence of smell of ammonia over the slits after injection showed that it was well sealed, (2) that the aqueous ammonia injector knives did good rather than harm to the sward (Table 4), and (3) most importantly, that more N was recovered from aqueous than from anhydrous ammonia.

Aqueous urea and aqueous ammonia differed little in performance when injected in the same way in 1970. However, one experiment was not sufficient for a proper assessment of aqueous urea for grass, though we showed (1972) that it was equally as good as aqueous ammonia for barley.

We obtained no evidence that injected N gave more grass than broadcast N did during dry weather, and none to justify giving more than 375 kg N/ha. Grass given 375 kg N/ha removed approximately 3 kg of P, 26 kg of K and 2 kg of Mg per tonne of dry matter produced; these removals of P and K agree closely with those by short duration leys at Rothamsted which were given a total of 340 kg N/ha for three cuts (Widdowson, 1968). It is usually considered that for stock fed largely on grass the dry matter should contain at least 0·2% Mg as a safeguard against hypomagnesaemia. Table 6 shows that, on average, grass at the first cut contained less, and at the second and third cuts no more than this minimum amount.

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Appendix Table 1. *The intended and actual amounts (kg/ha) of N applied as each fertilizer in each experiment*, 1966–70

	Experiments																
Experiment...	West Barnfield		Bones Close				Parklands				Appletree				Bones Close		
Year...	1966		1967				1968				1969				1970		
Fertilizer	An.	N-C	An.	Aq.	An.	Aq.	An.	Aq.	An.	Aq.	An.	Aq.	An.	Aq.	An.	Aq.	U
	(spring)		(autumn)*		(spring)		(autumn)*		(spring)		(autumn)*		(spring)		(spring)		
Intended amount	Actual amounts applied																
125	125	125	152	116	238	127	—	—	—	—	127	126	120	131	86	122	121
250	306	306	285	249	351	254	262	275	257	262	262	246	266	244	256	247	251
375	370	370	418	375	402	389	366	389	360	374	378	393	376	368	370	367	374
500	491	491	684	520	489	506	499	531	523	495	498	499	497	529	506	511	511
625	—	—	—	—	—	—	601	649	609	611	—	—	—	—	—	—	—

An. = anhydrous ammonia. Aq. = aqueous ammonia. N-C = 'Nitro-Chalk'. U = aqueous urea.
* Autumn of previous year.

Appendix Table 2. *Yields (t/ha) of dry grass given by injecting either anhydrous ammonia or aqueous ammonia or aqueous urea and by broadcasting 'Nitro-Chalk' in five experiments,* 1966–70

		An. in spring				N-C in spring				N-C, ⅓ for each cut				
		West Barnfield experiment, 1966												
N applied, (kg/ha)*...	None	125	250	375	500	125	250	375	500	125	250	375	500	S.E.
1st cut	1·24 (±0·083)	2·13	3·05	2·91	3·14	4·46	4·63	4·82	4·57	2·82	4·03	4·46	4·50	±0·183
2nd cut	1·88 (±0·041)	2·07	2·48	2·64	2·79	2·64	4·19	4·53	4·38	3·75	4·93	4·79	4·72	±0·132
3rd cut	0·26 (±0·058)	0·29	0·19	0·23	0·23	0·20	0·50	0·89	1·91	1·30	3·02	3·35	3·44	±0·133
		Bones Close experiment, 1967												
		An. in autumn				Aq. in autumn				N-C, ⅓ for each cut				
N (kg/ha)*...	None	125	250	375	500	125	250	375	500	125	250	375	500	
1st cut	4·67 (±0·228)	5·95	6·43	6·94	7·18	6·73	6·69	6·89	7·10	5·48	6·55	6·06	6·41	±0·322
2nd cut	0·79 (±0·107)	1·03	1·29	2·10	2·07	1·24	2·67	2·80	3·00	1·98	2·95	3·09	2·87	±0·151
3rd cut	0·29 (±0·102)	0·31	0·38	0·73	0·94	0·33	0·84	1·51	2·36	1·30	2·20	2·57	2·86	±0·143
		An. in spring				Aq. in spring				N-C in spring				
1st cut	—	6·25	5·97	6·41	5·94	5·72	6·17	6·09	6·10	6·40	5·77	6·07	6·26	±0·322
2nd cut	—	2·06	2·46	2·32	2·58	1·54	2·27	2·86	2·99	1·57	2·26	2·54	3·22	±0·151
3rd cut	—	0·58	0·97	1·41	1·76	0·41	0·68	1·69	2·84	0·36	0·65	1·23	2·66	±0·143
		Parklands experiment, 1968												
		An. in autumn				Aq. in autumn				N-C, ⅓ for each cut				
N (kg/ha)*...	None	250	375	500	625	250	375	500	625	250	375	500	625	
1st cut	2·66 (±0·139)	4·28	4·48	4·58	4·20	4·29	4·44	4·59	4·81	4·27	4·20	4·12	4·33	±0·196
2nd cut	2·28 (±0·107)	3·00	3·30	3·35	3·31	3·44	3·43	3·56	3·25	3·16	3·33	3·36	3·21	±0·151
3rd cut	2·95 (±0·163)	2·89	2·67	2·50	2·77	2·95	2·81	3·02	2·74	2·45	2·55	2·32	2·47	±0·231
		An. in spring				Aq. in spring				N-C in spring				
1st cut	—	4·49	3·99	3·93	4·10	4·24	4·39	4·34	4·30	3·90	3·84	4·38	4·20	±0·196
2nd cut	—	3·50	3·49	3·59	3·50	3·29	3·58	3·44	3·21	3·18	3·60	3·49	3·26	±0·151
3rd cut	—	2·75	2·79	2·94	2·79	2·92	3·02	2·85	2·70	2·72	2·89	2·51	2·66	±0·231

Appendix Table 2 (*cont.*)

Appletree experiment, 1969

		An. in autumn				Aq. in autumn				N-C, $\frac{1}{3}$ for each cut				
N (kg/ha)* . . .	None	125	250	375	500	125	250	375	500	125	250	375	500	
1st cut	2·49 (±0·123)	2·99	3·70	4·77	4·80	5·18	4·84	5·35	5·13	4·26	4·95	4·94	5·14	±0·174†
2nd cut	1·37 (±0·121)	1·48	1·55	2·26	3·11	1·88	3·11	3·60	3·46	2·91	3·68	4·00	3·40	±0·171†
3rd cut	0·18 (±0·042)	0·19	0·20	0·26	0·48	0·26	0·30	0·74	1·19	1·07	1·54	1·49	1·19	±0·060†
		An. in spring				Aq. in spring				N-C in spring				
1st cut	—	4·64	4·63	4·80	4·66	5·10	4·90	5·09	5·05	4·96	4·90	4·72	4·65	±0·174
2nd cut	—	2·33	2·66	2·90	3·83	2·24	3·46	3·94	3·79	2·00	3·62	3·95	4·05	±0·171
3rd cut	—	0·24	0·27	0·45	0·72	0·23	0·40	0·66	1·18	0·25	0·43	0·72	1·04	±0·060

Bones Close experiment, 1970

		U in spring								N-C, $\frac{1}{3}$ for each cut				
N (kg/ha)* . . .	None	125	250	375	500	125	250	375	500	125	250	375	500	
1st cut	4·60 (±0·223)	5·44	5·57	5·58	5·26	—	—	—	—	5·34	5·94	6·03	5·78	±0·223
2nd cut	0·39 (±0·121)	0·97	1·39	1·30	1·24	—	—	—	—	1·09	1·28	1·36	1·56	±0·121
3rd cut	0·27 (±0·157)	0·49	1·89	2·30	2·24	—	—	—	—	1·65	2·36	2·26	2·25	±0·157
		An. in spring				Aq. in spring				N-C in spring				
1st cut	—	5·41	4·87	5·22	4·97	5·82	5·72	5·66	5·81	5·86	5·41	5·45	5·22	±0·223‡
2nd cut	—	1·00	1·06	1·40	1·19	0·94	1·16	1·32	1·46	0·95	1·26	1·48	1·46	±0·121‡
3rd cut	—	0·50	1·81	2·20	2·46	0·46	1·38	1·98	2·70	0·65	1·63	2·16	2·05	±0·157‡

An. = anhydrous ammonia. Aq. = aqueous ammonia. U = aqueous urea. N-C = 'Nitro-Chalk'.
* Intended amounts; actual amounts applied are given in Appendix Table 1.
† These errors do not apply to yields with anhydrous ammonia in autumn.
‡ These errors do not apply to yields with anhydrous ammonia in spring.

Appendix Table 3. *Percentages of N in dry grass (mean of three cuts), amounts of N (kg/ha) removed in three cuts and the apparent percentage recoveries of N from anhydrous ammonia, aqueous ammonia, aqueous urea and 'Nitro-Chalk' in five experiments,* 1966–1970

		West Barnfield experiment, 1966												
		An. in spring				N-C in spring				N-C, ⅓ for each cut				
N (kg/ha)* . . .	0	125	250	375	500	125	250	375	500	125	250	375	500	S.E.
Mean % N in dry grass	1·64	1·68	1·82	2·13	2·04	1·84	1·99	2·70	3·12	1·83	2·02	2·36	3·00	—
N (kg/ha) in three cuts	48·7 (±3·12)	65·6	94·5	124·5	127·5	127·1	204·2	303·1	368·6	140·1	243·5	296·9	383·2	±14·41
Apparent % recovery of N given	—	13	15	20	16	63	51	69	65	73	64	67	68	—
		Bones Close experiment, 1967												
		An. in autumn				Aq. in autumn				N-C, ⅓ for each cut				
N (kg/ha)* . . .	0	125	250	375	500	125	250	375	500	125	250	375	500	
Mean % N in dry grass	2·00	1·88	2·05	2·37	2·46	2·04	2·32	2·66	2·99	1·99	2·36	2·70	2·68	—
N (kg/ha) in three cuts	102·9 (±10·57)	132·9	175·7	242·6	266·6	171·6	249·1	310·4	379·0	172·4	275·8	307·5	323·5	±14·93
Apparent % recovery of N given	—	20	26	33	24	59	59	55	53	55	69	54	44	—
		An. in spring				Aq. in spring				N-C in spring				
Mean % N in dry grass	—	2·51	2·67	2·82	2·73	2·22	2·45	2·77	3·08	2·08	2·47	2·94	3·41	—
N (kg/ha) in three cuts	—	245·4	267·9	300·1	295·2	191·9	246·2	309·0	377·8	185·7	239·6	310·5	438·5	±14·93
Apparent % recovery of N given	—	60	47	49	39	70	56	53	54	66	54	55	67	—
		Parklands experiment, 1968												
		An. in autumn				Aq. in autumn				N-C, ⅓ for each cut				
N (kg/ha)* . . .	0	250	375	500	625	250	375	500	625	250	375	500	625	
Mean % N in dry grass	2·13	2·62	28·9	3·26	3·37	2·65	3·06	3·45	3·54	2·59	2·97	3·24	3·59	—
N (kg/ha) in three cuts	170·2 (±9·42)	271·2	303·2	341·1	344·2	289·0	331·1	386·0	386·3	254·3	289·4	311·2	356·7	±13·33
Apparent % recovery of N given	—	38	36	34	29	43	41	41	33	34	32	28	30	—
		An. in spring				Aq. in spring				N-C in spring				
Mean % in dry grass	—	2·58	2·96	3·25	3·31	2·83	2·99	3·56	3·60	2·87	3·15	3·63	3·63	—
N (kg/ha) in three cuts	—	275·8	304·3	338·8	344·0	300·4	336·8	381·5	366·7	288·3	327·9	383·9	372·1	±13·33
Apparent % recovery of N given	—	41	37	32	28	50	44	43	32	47	42	43	32	—

Appendix Table 3 (*cont.*)

Appletree experiment, 1969

		An. in autumn				Aq. in autumn				N-C, ⅓ for each cut				
N (kg/ha)*...	0	125	250	375	500	125	250	375	500	125	250	375	500	
Mean % N in dry grass	1·71	1·77	1·95	2·11	2·44	1·93	2·24	2·74	2·91	1·89	2·35	2·68	2·93	—
N (kg/ha) in three cuts	65·4 (±8·78)	79·2	110·2	163·5	207·3	143·4	200·3	270·6	287·2	151·6	233·0	260·5	268·6	±12·43†
Apparent % recovery of N given	—	11	17	26	28	62	55	52	44	69	67	52	40	—
		An. in spring				Aq. in spring				N-C in spring				
Mean % N in dry grass	—	2·16	2·06	2·30	2·65	1·95	2·18	2·56	2·94	1·95	2·30	2·62	3·02	—
N (kg/ha) in three cuts	—	166·9	163·3	190·2	251·6	153·2	200·9	259·4	303·9	143·4	213·2	247·7	299·6	±12·43
Apparent % recovery of N given	—	85	37	33	37	67	56	53	45	62	59	48	47	—

Bones Close experiment, 1970

		U in spring								N-C, ⅓ for each cut				
N (kg/ha)*...	0	125	250	375	500	125	250	375	500	125	250	375	500	
Mean % N in dry grass	1·97	2·52	2·89	3·13	3·25	—	—	—	—	2·32	2·68	2·98	3·17	—
N (kg/ha) in three cuts	92·1 (±10·08)	188·7	266·5	287·1	285·8	—	—	—	—	178·2	242·9	272·3	286·0	±10·08
Apparent % recovery of N given	—	80	69	52	38	—	—	—	—	69	60	48	39	—
		An. in spring				Aq. in spring				N-C in spring				
Mean % N in dry grass	—	2·38	2·93	3·04	3·07	2·34	2·73	3·02	3·05	2·31	2·90	3·11	3·28	—
N (kg/ha) in three cuts	—	175·0	237·0	264·2	264·4	181·6	238·7	278·0	310·9	177·6	244·8	285·8	291·0	±10·08‡
Apparent % recovery of N given	—	96	57	46	34	73	59	51	43	68	61	51	40	—

An. = anhydrous ammonia. Aq. = aqueous ammonia. U = aqueous urea. N-C = 'Nitro-Chalk'.
* Intended amounts; actual amounts applied are in Appendix Table 1.
† Error does not apply to N in grass given anhydrous ammonia in autumn.
‡ Error does not apply to N in grass given anhydrous ammonia in spring.