HGCA

PROJECT REPORT No. 73

NITROGEN PREDICTION

I. REVIEW OF CURRENT ADVICE ON CEREAL CROP REQUIREMENTS
II. EFFECTS OF PREVIOUS CROPPING ON RESPONSES OF WINTER WHEAT TO APPLIED NITROGEN

APRIL 1993

PRICE £13.00

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II. EFFECTS OF PREVIOUS CROPPING ON RESPONSES OF WINTER WHEAT TO APPLIED NITROGEN

by

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Final report of a four year project at ADAS Cambridge. The work commenced in May 1987 and was funded by a grant of £124,427 from the Home-Grown Cereals Authority (Project No. 0023/3/87).

CONTENTS

Part One : Summary answers to questions addressed in the Nitrogen Prediction Papers

Part Two : Unpublished Nitrogen Prediction Papers (*)

ABSTRACT

The Project had two elements; a review and an experiment.

1. **The review** was made through a sequence of 16 scientific papers, with additional press articles, giving information which forms the basis for advice on applying nitrogen to cereal crops. These are summarised as a series of questions with short answers. Unpublished papers are reproduced fully in Part Two[1].

2. **The experiment** used winter wheat crops to test whether responses to applied nitrogen were different after peas, beans and cereals and, if so, whether variation could be related to characteristics of previous crops. This work is fully reported as Paper 6 of Part Two.

Conclusions :

1. In deciding how to apply nitrogen to cereals, the tendency of growers is first to choose the fertiliser, then the amount and lastly the timing of their applications. Their choices are influenced as much by commercial considerations as by growing conditions.

2. If perfect recommendations were possible for all wheat crops, growers would benefit by about £20/ha. Current recommendation schemes are similarly poor because they fail to identify fields with aberrant responses to N.

3. Differences in effectiveness between urea and ammonium nitrate are normally too small to be proven by experiment.

4. Organic matter content is a useful yardstick of the nitrogen supplying power of Fenland soils, but applications of nitrogen should also account for sub-soil acidity and residual effects of previous crops.

5. Measurements in spring show that sugar beet leaves behind no more N than cereals, but oilseed rape or peas leave about an extra 30 kg/ha of 'available' N. Despite the greater yields after oilseed rape and peas, optimum amounts of fertiliser nitrogen are about 50 kg/ha less than after cereals or sugar beet.

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[1] *Readers having difficulty obtaining copies of published papers may write to the author for reprints.*

6. Measurements in autumn show about 25 kg/ha extra 'available' N after peas or about 10 kg/ha after beans but eventually their nitrogen contributions to a succeeding cereal crop are very similar.

7. Wheat appears to recover an average of 60% of the N that is applied, but this varies between about 40% and 90%. There is evidence that large crops recover large proportions of the fertiliser N that they receive.

8. The green surface area of a wheat crop appears to be directly related to the N it contains. If a canopy needs to expand by 1 ha, a crop needs to take up about 30 kg extra N.

9. Wheat crops appear to reach a limit for N uptake; further increases in fertiliser N give little further expansion of leaf area or increase in growth.

10. Where all quality characters of wheat crops grown for breadmaking are expected to be satisfactory other than protein, it is profitable to apply about 25 kg/ha extra N.

11. Only about 30% of wheat crops grown for breadmaking have grain protein concentrations where extra N would be expected to increase premium payments. Analysis of flag leaves might help identify which crops these are.

12. Apparent recovery of sprayed N can be improved by making small applications. It may be worth adding urea N to sprays applied for other purposes.

13. When the protein in wheat flour has been given a boost by extra applications of N this is not always translated into larger loaves.

14. It is best to estimate the optimum N amount for a cereal crop from a multi-level N experiment, fitting a curve to describe the yield response. Models help to justify how a particular fertiliser policy has been chosen, because models are likely to provide the best representation of what is understood of soil and crop processes.

15. Sub-optimal amounts of N have a small effect on the nitrate residues left in the soil by cereals, but effects can be large where N applications are super-optimal.

BY WHAT LOGIC IS NITROGEN APPLIED TO CEREALS ?

1. What is the sequence of decisions when cereal growers consider applying nitrogen ?

Having determined the form of fertiliser nitrogen for the farm it is normal to consider :

whether to apply autumn N, then the total amount of spring and summer fertiliser nitrogen, the number of nitrogen applications (between which the total amount should be divided), the amount and timing of the early spring nitrogen, the timing of the principal application, and (when wheat is being grown for breadmaking) whether to apply an extra amount of nitrogen late, and the form, method and exact timing of any late application.

2. How do growers most commonly apply N to cereals ?

Surveys show that *normal* practice is to apply no N in autumn and, using prilled ammonium nitrate, to provide a total of 190 kg/ha N for winter wheat, 150 kg/ha N for winter barley and 100 kg/ha N for spring barley, divided between two or three applications, the first being made in early spring at about 40-50 kg/ha N and the others focussed shortly before the time stem extension starts. Almost half the wheat crops grown for breadmaking receive an additional 30-50 kg/ha N normally broadcast as ammonium nitrate prills during May.

3. In what way have decisions on applying N changed in recent years ?

Ammonium nitrate remains the dominant fertiliser; but use of prilled urea now extends to about 10% of farms. The trends are for use of N in autumn to become minimal in the early '90s. Total N applications to cereals in spring have stabilised, having increased over the decade to 1985 by 100 kg/ha for winter wheat, 60 kg/ha for winter barley and 30 kg/ha N for spring barley. The number of applications has changed with the total amounts applied, more N is used in early spring, but little has changed with later applications.

4. What factors have most influence on nitrogen decisions now ?

Adjustments to past farm practice are influenced by recent farm performance and market trends as well as by comparisons of prices, convenience, and efficacy of N fertilisers as shown by experiment. Soil and crop condition (such as the previous cropping, the presence of straw and the success of establishment) influence N use on a field by field basis.

5. How much do nitrogen decisions matter ?

The costs or benefits of some common decisions on the use of N can be calculated from experiments. They show net costs of £10-50/ha from choosing the wrong form of fertiliser, £5/ha from using autumn N, £10/ha (or so) from inaccurate total N amounts, £20/ha from not dividing the spring application and £20/ha due to mistiming the main dressings; on average, there appears little net effect of applying extra N late.

6. What are the main uncertainties affecting decision-taking on nitrogen ?

The particular soil, crop and weather conditions governing efficacy of each dressing are in doubt. At present, the third of three equal dressings made to winter wheat accounts for only 5% of its grain yield. Benefits should come from further research to improve on this, through better choice of fertiliser and of application techniques, better management of growth and crop condition and thus susceptibility of the crop to pathogens.

Reference - Paper 1 : (see pages 29 - 43)

SYLVESTER-BRADLEY, R. (1989). Deciding how to apply nitrogen to cereals. Paper written in support of H-GCA funded Review of 'Benefits to the Industry from the application of knowledge on crop growth and development'.

NITROGEN RECOMMENDATIONS : HOW RELIABLE ARE THEY ?

1. So much has been spent of N research; how much further can predictions be improved ?

If perfect recommendations were possible for all wheat crops, on average growers would benefit by about £20/ha.

2. Various countries and organisations have different systems for setting N amounts; how do they compare ?

All recommendation systems seek to provide fertiliser N sufficient to make up any shortfall between crop demand for N and soil supply of N. Methods of assessing demand and supply differ, but the net difference between recommendation schemes is small. Analysis shows that all current realistic recommendation schemes are equally poor, mainly because they do not identify fields where weed competition, diseases or other factors which cause particularly restricted or enhanced yields subsequently result in aberrant crop responses.

3. Since N advice is always uncertain, can the risk of loss be minimised by applying N generously ?

There is only a slight economic advantage from applying more N than has been shown to be optimal for a particular circumstance. The most economic policy was to exceed the average optimum by just 6 kg/ha N.

Reference - Paper 2 :

SYLVESTER-BRADLEY, R., BLOOM, T.M., VAIDYANATHAN, L.V. & MURRAY, A.W.A. (1987). *The quest for the optimum: a comparison of N recommendation systems for winter wheat*, in Proceedings of Third Meeting of NW Europe Study Group for the Assessment of N Fertiliser Requirements, Copenhagen, pp 113-133.

WHICH IS BETTER - UREA OR AMMONIUM NITRATE ?

1. Do urea and ammonium nitrate give different yields ?

No, differences are normally too small to be proven. On 14 fields with shallow chalk soils ammonium nitrate gave the better *average* yield, by 0.09 t/ha. On other soils urea gave the better *average* yield by 0.01 t/ha (Figure 1).

2. If urea has a yield penalty, how do the prices of grain and the fertiliser affect the choice ?

Using a grain price of £100/t, an ammonium nitrate price of £115/t, a grain yield of 7.5 t/ha and a target N rate of 200 kg/ha the price which urea must not exceed in order to justify its use can be calculated as follows:

Yield penalty from using urea %	*Break even price of urea £/tonne*
0	153
1	135
2	118
3	101
4	67

3. Are the risks of poor fertiliser performance reduced by making split applications ?

No. There was not a single case, out of 28 trials, where it proved advantageous to split the main urea dressing.

4. Is there a difference in grain protein concentrations from urea and ammonium nitrate ?

Yes, grain protein concentrations with urea are slightly smaller than with ammonium nitrate. The average difference was 0.25% protein in trials with normal amounts of applied N.

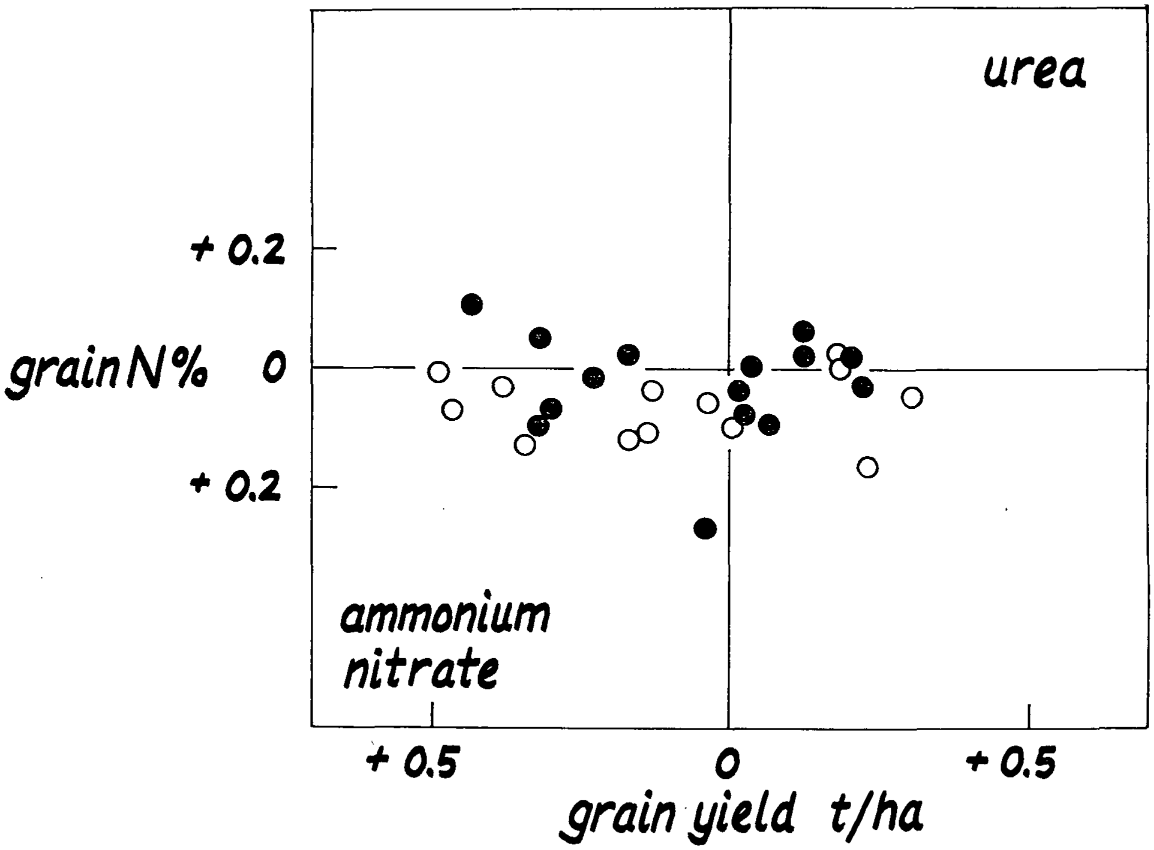

Figure 1. *The difference in grain yield and grain nitrogen concentration between urea and ammonium nitrate treatments in 28 cereal trials conducted from 1982-1985 on soils classed as chalky (open circles) and not chalky (closed circles).*

Reference - Paper 3 : (see pages 45 - 55)

ARCHER, J.R. & LLOYD, A. (1989). Comparison of ammonium nitrate and urea solid nitrogen top dressing for Winter Cereals. Paper prepared for later publication.

APPLYING NITROGEN TO WINTER WHEAT ON ORGANIC SOILS

1. Fen soils give notoriously variable yields. Are nitrogen requirements on fen soils similarly variable ?

Yes, responses to fertiliser nitrogen range from nil to almost as much as on mineral soils.

2. What are the main causes of such variable performance ?

In a series of 35 experiments yields were affected by sub-soil acidity, insufficient soil moisture during grain filling ('poor finishing'), take-all infection, wheat bulb fly attack and manganese deficiency.

3. Is organic matter content a useful yardstick of the nitrogen supplying power of Fenland soils ?

Nitrogen responses tended to be small where soil organic matter contents were large, and also where the previous crop was potatoes or peas.

It appears best to scale the provision of fertiliser nitrogen from amounts similar to mineral soils where organic matter is <10% to nil where organic matter is >40%.

However, where the sub-soil is acid, responses tend to be unexpectedly large.

Reference - Paper 4 :

SYLVESTER-BRADLEY, R., MILLS, N.P. & CLEAL, R.A.E. (1988). The response of Winter Wheat to fertiliser nitrogen on organic and peaty soils in the Fens, 1981-1987. *Paper presented at 5th Workshop on Nitrogen in Soil, Silsoe College, 13-14 December 1988.*

HOW DO BREAK CROPS ALTER NITROGEN USE BY CEREALS ?

1. How much N do break crops normally leave in the soil, available for a following cereal ?

Measurements in spring show that sugar beet leaves no more N than cereals, but oilseed rape or peas leave about an extra 30 kg/ha 'available' N.

2. What yield advantage is there from 'breaking' a sequence of cereal crops ?

There tends to be no yield advantage from breaking a cereal sequence with sugar beet.

However, a break crop of peas or oilseed rape results in about 1 t/ha extra grain in a following wheat crop.

3. How much allowance in N use can be made when a cereal follows a break ?

No adjustment should be made after sugar beet; optimum nitrogen levels are similar to those after cereals.

Despite the greater yields after oilseed rape and peas, optimum amounts of fertiliser nitrogen are approximately 50 kg/ha less than after a cereal.

4. Does a break give wheat a protein boost ?

Grain protein concentrations are very similar after cereals and after break crops, if given identical amounts of fertiliser nitrogen.

Thus, if an allowance in fertiliser application is made for soil nitrogen residues from peas or oilseed rape, the grain protein concentration tends to be *less*, not more, than after a cereal.

TABLE *showing effects of break crops on performance of winter wheat. (After rape or peas each value is an average from 30 trials between 1981 and 1985; after sugar beet each value is an average from 11 trials between 1985 and 1986.)*

Winter Wheat grown after	**Cereal**	**Break** *(differences)*
With breaks of oilseed rape or peas on clay loams		
'Soil' N in spring (kg/ha)	106	+29
Optimum applied N (kg/ha)	198	-52
Grain yield at optimum N (t/ha)	8.18	+0.98
Grain N at 240 kg/ha applied N (%)	2.22	-0.05
Grain N at optimum applied N (%)	2.05	-0.11
With breaks of sugar beet on sandy loams or sandy clay loams		
'Soil' N in spring (kg/ha)	57	-2
Optimum applied N (kg/ha)	200	-5
Grain yield at optimum N (t/ha)	8.51	-0.36
Grain N at 240 kg/ha applied N (%)	2.20	+0.03
Grain N at optimum applied N (%)	2.11	-0.03

Reference - Paper 5 :

VAIDYANATHAN, L.V., SYLVESTER-BRADLEY, R., BLOOM, T.M. & MURRAY, A.W.A. (1987). Effects of previous cropping and applied N on grain nitrogen content of winter wheat. *Aspects of Applied Biology* **15**, *Cereal Quality*, 227-237.

APPLYING NITROGEN TO WINTER WHEAT AFTER PEAS AND BEANS

1. Do nitrogen residues left by peas and beans benefit a following cereal crop equally ?

Yes. Measurements in autumn show extra 'available' N of about 25 kg/ha after peas and about 10 kg/ha after beans. Where soils are heavy enough to be retentive, these residues carry over for the next cereal crop. However, nitrogen appears be released more slowly from bean residues than from pea residues; eventually their nitrogen contributions to a succeeding cereal crop are very similar.

2. How does the 'break effect' on yield compare, when cereals follow peas or beans ?

Averaged over about 30 comparisons, there was about 1 t/ha extra grain after beans and about 1.25 t/ha extra grain after peas.

3. How should nitrogen applications be adjusted for cereals after peas, and after beans ?

The smaller responses of wheat after legumes than following a cereal indicate that an allowance of 20-25 kg/ha N should be made for the legume effect.

The differences between beans and peas are not sufficient to be distinguished.

Reference - Paper 6 : (see pages 55 - 89)

SYLVESTER-BRADLEY, R. & CROSS, R. B. (1991) Nitrogen residues from peas and beans and the response of the following cereal to applied nitrogen. *Final Report of the experimental work funded by the H-GCA under this Research Contract.*

HOW COMPLETELY DO CEREALS RECOVER THE NITROGEN THEY ARE GIVEN ?

1. How much of their fertiliser N do cereals recover ?

Taking 'recovery' as the *net* effect on crop N from applying fertiliser N, wheat appears to recover an average of 60% of the N that is applied, but this varies between about 40% and 90%.

2. Does the proportion of fertiliser N recovered depend on how much is applied ?

There is a wide range of N amounts over which the recovery is very similar (Figure 2).

However, as N applications are increased to exceed a certain (normally large) amount, very little additional N is recovered. Thus, large N applications tend to result in disproportionately large soil N residues.

3. What can be done to maximise the recovery of fertiliser N ?

There is evidence that larger crops recover larger proportions of their fertiliser N. Any practice which encourages crop growth is likely to improve N recovery.

However, there appear to be other factors controlling N recovery which are as yet unidentified.

Reference - Paper 7 :

BLOOM, T.M., SYLVESTER-BRADLEY, R., VAIDYANATHAN, L.V. & MURRAY, A.W.A. (1988). *Apparent recovery of applied N by winter wheat*, in Efficiency of Nitrogen Use, eds. D.S. Jenkinson & K.A. Smith. Elsevier, London, pp 27-37.

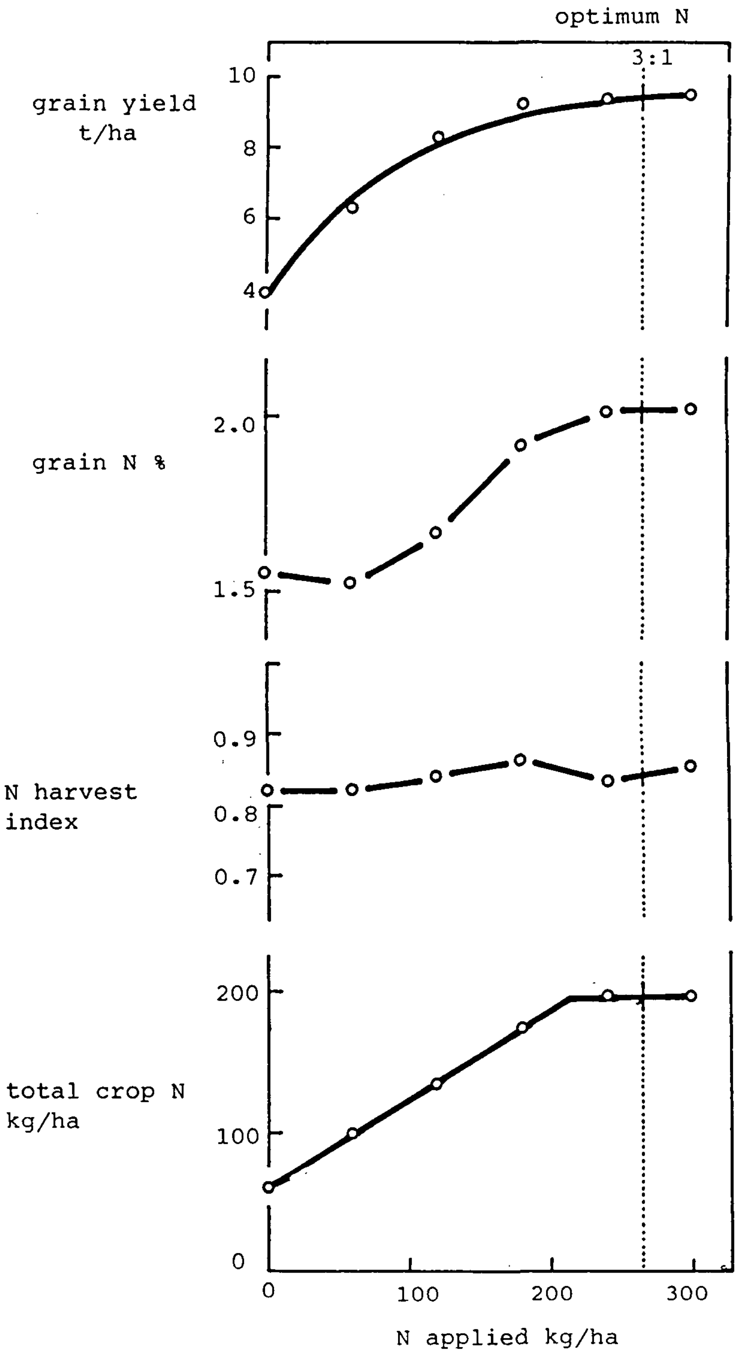

Figure 2. *Effect of applied nitrogen on grain yield, grain N%, N harvest index and total (above ground) crop N of winter wheat cv. Norman grown at Gestingthorpe, Essex, in 1984. Apparent recovery of the optimum amount (slope of the dashed line) was 50%.*

HOW IS IT THAT NITROGEN INCREASES GRAIN YIELD ?

1. How is it that nitrogen supply seems so crucial to producing good grain yields ?

Nitrogen applications encourage the expansion of green photosynthetic tissues of the crop.

Formation of the material for grain growth depends on photosynthesis, driven by the energy from sunlight; so the more green tissue there is, the more solar energy will be intercepted, and the more the grains will grow.

2. Why should the improvements in yield tail off as N applications are increased ?

There is a point at which the crop appears to reach its capacity for N uptake; extra fertiliser N causes little further N uptake. Hence little further expansion of leaf area.

Even before this point, each increase in leaf area increases the degree to which other leaves become shaded. Eventually a point can be reached where any extra leaf shades an equivalent area of leaf already formed, so no extra radiation is intercepted.

Also, by applying nitrogen, tissue expansion may be such that the crop structure becomes weak and unable to absorb and dissipate the energy from wind and rain without lodging. Lodging inhibits light from satisfactorily penetrating the green crop canopy.

Also, expanded tissues with large protein concentrations are prone to infection by pathogens.

Reference - Paper 8 :

SYLVESTER-BRADLEY, R., SCOTT, R.K. & STOKES, D.T. (1990) A physiological analysis of the diminishing responses of winter wheat to applied nitrogen. 1. Theory. *Aspects of Applied Biology* **25**, *Cereal Quality II*, 277-287.

WHAT SIMPLE RULES MIGHT SUMMARISE THE WAY NITROGEN AFFECTS CEREALS ?

1. How much of the sun's energy does winter wheat convert to growth, and ... does nitrogen affect this ?

There is a fairly constant amount of dry material formed for each unit of energy intercepted by crops. On a bright summer's day (with 19 MJ/m^2 of total radiation) crops with a complete green canopy will grow by about 0.25 t/ha, whatever their stage of development.

There are indications that applying N may cause green canopies to become more efficient.

2. How large does the crop's green canopy need to be to intercept most of the sunlight ?

Beer's Law allows us to calculate this: 3 ha of green canopy per ha of land intercepts about 70% of solar radiation; 6 ha/ha intercepts about 90%.

3. How much nitrogen does the crop need if its green canopy ought to be enlarged ?

The green surface area of a wheat crop appears to be directly related to the N it contains. If canopy expansion of 1 ha is required, the crop needs to take up about 30 kg extra N.

4. How does nitrogen alter the canopy, in terms of stems and leaves ?

The main way that N increases canopy size is by encouraging more tillers to survive. Each tiller and leaf is not much altered in size by N. Each mainshoot achieves about 125 cm^2 of green surface.

5. What happens to all the crop's nitrogen as its green canopy dies ?

N uptake is all but complete at flowering time; but by harvest three quarters of the crop's N has been redistributed to the grain. Here is a conundrum for, as N is withdrawn for grain protein formation, the canopy must lose its greenness and the ability to enhance grain growth.

Reference - Paper 9 :

SYLVESTER-BRADLEY, R., STOKES, D.T., SCOTT, R.K. & WILLINGTON, V.B.A. (1990) A physiological analysis of the diminishing responses of winter wheat to applied nitrogen. 1. Evidence. *Aspects of Applied Biology* 25, 289-300.

HOW SHOULD NITROGEN BE APPLIED TO MAXIMISE THE PROFITS FROM BREAD-MAKING WHEATS ?

1. Is it worth applying more N than would otherwise be applied to optimise yield ?

Not always. But, where rejections for quality characters such as Hagberg falling number are not expected, about 25 kg/ha extra N seems optimal.

2. Does the size of the (expected) premium for quality affect best use of N on bread-making varieties ?

Only when the grain protein premium is expected to exceed £24/t is it worth applying more than 25 kg/ha extra N.

3. Is the best policy for use of N affected by the way that premium payments are decided ?

Most common premium payment schemes do not affect the best amount of extra N to apply.

If payments were made on a continuous sliding scale from 10% protein to 12% grain protein (a situation which would only be likely where grain is blended before sale) then it would be just best to apply 50 kg/ha extra N.

Reference - Paper 10 :

SYLVESTER-BRADLEY, R. & GEORGE, B. (1987). Effect of quality payments on the economics of applying N to winter wheat. *Aspects of Applied Biology* 15, *Cereal Quality*, 303-318.

CAN WE TELL WHICH CROPS ARE GOING TO NEED A PROTEIN BOOST ?

1. To start with, what are the odds of getting a premium payment ?

Only about a third of East Anglian wheat crops grown for breadmaking have grain protein concentrations greater than 11%. About a further 30% of crops have protein concentrations in the range 10.5-11.0%, where extra applied N could be used to increase protein concentrations to a level which would qualify for premium payments.

2. How often does the premium payment hinge on grain protein concentration ?

In a minority of cases. When Hagberg falling number or other quality parameters are adverse, grain protein concentration has small influence on premiums, even for the 30% of crops with protein concentrations in the range 10.5-11.0%

3. Could crop analysis be used to pick out crops likely to benefit from a late N application ?

Yes, crops with large amounts of N per flag leaf blade (sampled just as they became fully emerged) tended to have large grain protein concentrations at harvest.

However, seasonal effects also need to be known because the best crops to treat with extra N can be those with low protein expectations in one year, and high protein expectations the next.

Reference - Paper 11 :

SYLVESTER-BRADLEY, R. (1990) Prediction of grain protein concentration in East Anglian wheat crops by analysis of the nitrogen in their flag leaves. *Aspects of Applied Biology* 25, *Cereal Quality II,* 261-265.

CAN CROP UPTAKE OF SPRAYED N BE IMPROVED ?

1. How effective is sprayed N in boosting grain protein ?

If, as is commonly found, 40 kg/ha extra N applied as a urea spray during grain filling increases the protein concentration of 8 t/ha grain by 0.75%, then 30% of the applied N has apparently been recovered.

2. What methods might improve the uptake of sprayed N ?

Apparent recovery of sprayed N can be improved by making small applications: recovery of N was about 30% of a 30 kg/ha application but about 60% of a 10 kg/ha N application. Three successive applications of 10 kg/ha N gave an intermediate recovery of about 45%.

Canopy disturbance during spraying, using a 'crop tilter', does not seem to improve recovery of sprayed N although, unexpectedly, there seem to be some occasional improvements in grain yield.

3. Is it worth altering the way N is normally sprayed onto bread-making wheat crops ?

The improvements in recovery of N are too small to justify making an increased number of smaller N applications. However, one might consider including some urea, when the sprayer is being used for other purposes.

Reference - Paper 12 :

SYLVESTER-BRADLEY, R., ROCHFORD, A.D. & RULE, J.S. (1990) Effects of canopy disturbance whilst spraying urea on grain yield and nitrogen uptake by winter wheat. *Aspects of Applied Biology* 25, *Cereal Quality II,* 309-313.

DOES EXTRA NITROGEN APPLIED TO BREADMAKING WHEAT BENEFIT THE BAKER ?

1. Is the extra protein, measured after extra N has been sprayed on wheat, removed by milling ?

No, there is no evidence that, through the milling process, more N is lost from the grain of sprayed crops than from grain of unsprayed crops.

2. When the protein in wheat flour has been given a boost, is this translated into larger loaves ?

It all depends. In recent dry seasons of 1988, 1989 & 1990 trials have shown boosted protein normally to be associated with larger loaves. But over the 'poor' seasons of 1985, 1986 & 1987 loaf volume was only improved once out of 12 trials.

3. What might stop loaf volumes from reflecting grain protein concentrations ?

a. The grain might be damaged by drying, or include a contaminant variety, or have a low Hagberg falling number.
b. The N analysed might not all be protein-N.
c. The baking process may only be responsive over a particular range of protein concentrations.
d. Changes in protein concentration may be linked to other changes in the grain which affect baking performance.

4. Do bakers need to make payments according to grain protein concentration ?

It appears that in some seasons grain protein concentrations are generally adequate for contemporary breadmaking processes so that the thresholds set for acceptable grain could be less stringent, the costs of production could be reduced, and so would justify smaller premiums.

Reference - Paper 13 :

SYLVESTER-BRADLEY, R. (1990) Does extra nitrogen applied to breadmaking wheat benefit the baker? *Aspects of Applied Biology* **25**, *Cereal Quality II,* 217-227.

HOW ARE THE MODELS WHICH ARE BEING DEVELOPED BY RESEARCHERS EXPECTED TO AFFECT NITROGEN ADVICE ?

1. *What progress has been made in N advice this century ?*

At the turn of the century the 'Board of Agriculture and Fisheries' considered that it was the farmers' duty to work out their own fertiliser requirements!

Now, we have comprehensive recommendations for all crops, sanctioned by Government, and based upon extensive research.

2. *How is the optimum amount of nitrogen best measured ?*

The most precise estimate of an optimum N amount comes from a multi-level N experiment; the yields can be described by fitting a curve (both the 'modified exponential', and the 'ratio of polynomials' work well) and the optimum can be found by differentiating the resulting equation.

Such a calculated optimum can nevertheless be quite uncertain, because the costs and benefits from N are often similar over a broad range of amounts of N.

3. *How do the new computer models of leaching and crop growth work ?*

A series of equations interlinked in a computer-program can form a 'model' of how we think cereals behave with respect to N.

Such a model may be too complex to check in every detail but its results can be compared to observations. Then we gain confidence that our understandings are expressed in a tenable way, because they lead to realistic predictions. However, current uncertainties in leaching and crop growth are such that different models could still give similar predictions.

4. What soil and crop processes are included in contemporary models ?

All models work out a balance between N added as fertiliser (and from other sources) and N taken away in crop produce; they then allow the excess N from one crop to influence the outcome for the next crop.

The more detailed models commonly work on a daily basis, rather than by season. These then include descriptions of :

- inputs of N in rain, and exchanges of ammonia N with the atmosphere,
- microbial transformations of N leading both to fixation of and release to the atmosphere,
- exchanges of ammonium N with clay particles,
- release of ammonium and nitrate N from crop residues and organic matter in the soil,
- movement of available N with the soil water,
- root development of the crop, uptake of available N by the crop, and crop growth.

5. How are computer models expected to improve N advice ?

Modelled advice can take into account more detail relating to a particular field than written or spoken advice.

It becomes easier to explain and justify how a particular course of action has been chosen if it was developed through a model, because the model is likely to be our best representation of what we understand of soil and crop processes.

Reference - Paper 14 :

SYLVESTER-BRADLEY, R., ADDISCOTT, T.M., VAIDYANATHAN, L.V., MURRAY, A.W.A., & WHITMORE, A.P. (1987). *Nitrogen advice for cereals: present realities and future possibilities.* Proceedings of the Fertiliser Society No. 263, 36 pp.

DO WE KNOW ENOUGH TO BLAME FERTILISERS FOR THE NITRATE IN DRINKING WATER ?

1. How does the N applied to cereals in spring affect amounts of leachable nitrate in autumn ?

Sub-optimal amounts of N have a small effect on nitrate residues left in the soil. However, effects can be large where N applications are super-optimal.

2. Do cereal growers use too much fertiliser nitrogen ?

Not often. But the main problem appears to be a reluctance to make full allowance for the N already available in the soil at the time the fertiliser is applied.

Sizeable soil N residues can come from previous break crops, organic manure applications or grass leys.

3. How might growers minimise the leachable nitrate in their cereal land ?

By minimising the microbial activity in soil which releases nitrate, through reducing and delaying subsoiling, ploughing or other soil cultivations, and through incorporating straw.

By maximising crop uptake in autumn through late harvests of root crops (or late killing off of potatoes or grass leys), earlier drilling of cereals, or use of cover crops.

Reference - Paper 15 : (see pages 90 - 105)

SYLVESTER-BRADLEY, R. & UNWIN, R. (1988). *Nitrogen losses and requirements in arable farming: the need for new knowledge.* Annex 5 to Special Topic Review on Nitrate Modelling, MAFF, London.

ARE THERE ANY NEW IDEAS FOR MAKING BETTER USE OF NITROGEN ?

Yes. The following is a synopsis of some further questions. These are subjects for further research. Proposals on these and other questions are being put to the Authority, to the industry and to Government.

1. *Can early sowings be used to catch more soil N without unduly increasing the risks of pests and diseases ?*

2. *What is it that controls the amount of newly applied N which is locked up in the soil ?*

3. *How is it that the N not recovered from fertiliser is the same fraction of a small N dressing as of one ten times as large ?*

4. *Might soil organisms be tricked into locking up less of the N that is applied in spring ?*

5. *What causes cereals to have a limit to the amount of N they can take up ?*

6. *Can the factors be identified which make large crops good at recovering fertiliser N ? Surely not all the factors that increase crop size will also cause better uptake of N ?*

7. *Conversely, can the factors be identified which make it appear that large crops need large amounts of fertiliser N ?*

8. *Do cereal canopies often become unnecessarily large when large amounts of N are added in spring ?*

9. Could cereal production be maintained at less cost if nitrogen applications were tied more tightly to crop and soil conditions ?

10. Could fertiliser practices be changed to give canopies so open, and thus less prone to disease, that fungicide costs could be reduced ?

11. If crops run out of N when soils are dry would the crop respond to sprayed N more effectively than prills ?

12. If as much attention was paid to the formulation of N sprays as is normally put into development of other sprayed agrochemicals, could they be made more effective than prilled N products ?

13. Does sprayed N result in less loss of N by leaching than prilled N ?

14. Might there be a way of using N to stop the crop losing its greenness during the grain filling phase ? And would this increase yield ?

15. Can the quality of grain for malting be sustained without accentuating the early applications of N that have attendant risks of losses by leaching ?

Reference - Paper 16 : (see pages 106 - 111 for Abstract)

SYLVESTER-BRADLEY, R. SCOTT, R.K. & WRIGHT C.E. (1990) *Physiology in the production and improvement of cereals.* Research Review No. 18. Home-Grown Cereals Authority, London, 156 pp.

DECIDING HOW TO APPLY NITROGEN TO CEREALS

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SUMMARY

Despite the crucial role of nitrogen in determining biological performance of cereal crops, its application depends on availability of money, fertiliser and trafficable ground as well as knowledge of nutrient function. Research on nitrogen nutrition is thus best targeted where uncertainties in such knowledge play a big part in farm decisions. For a common decision-taking structure this paper analyses the principal influences and the points at which new physiological research has scope to improve farm practice.

INTRODUCTION

This paper aims to analyse the factors affecting farm decisions on the application of fertiliser nitrogen to cereal crops in the UK.

The decisions and the order in which they are considered are:

1. The form of fertiliser nitrogen
2. Autumn nitrogen
3. Total amount of spring and summer fertiliser nitrogen
4. The number of nitrogen applications (between which the total amount is divided)
5. Amount and timing of early spring nitrogen
6. Timing of the principle application
7. Amount of nitrogen applied late (to wheat grown for breadmaking).
8. Form, method and time of late nitrogen applications (to wheat grown for breadmaking).

This decision-making structure is thought to be conventional, but it would often not be followed throughout. For example, it is thought normal that the decision on 'amount of nitrogen applied in spring and summer' *precedes and governs* the decision on its timing. However, some farms, particularly on the continent, decide on amounts *after* the times of application have been identified, and thus may allow changes in soil or crop conditions to have a greater influence on each decision.

Under the heading for each decision are five sub-sections in which is given a description of:

1. the normal result of the decision by UK farmers
2. how and why the result may have changed in recent years
3. the factors which have most influence on the result now
4. the importance of the decision to the decider
5. any physiological research which is seen to have a good chance of improving success of the decision.

This paper was prepared in support of the H-GCA funded review of 'Physiology in the production and improvement of cereals' (Sylvester-Bradley, Scott & Wright, 1990). The objective was to assist in identifying the research on nitrogen which is most likely to benefit the grower.

1. The form of fertiliser nitrogen

1.1 Prilled ammonium nitrate

1.2 There has been a steady decline in the use of compound fertilisers and an increased use of 'straights' because growers have sought greater flexibility in matching applications to crop requirements and soil supplies (estimated by analysis for P, K and Mg) and have needed to cut costs. A significant minority have been using liquid fertilisers. Liquid nitrogen is usually half ammonium nitrate and half urea. The choice of ammonium nitrate prills is reflected in vast investment in manufacturing plant so that a change is inhibited by the supply industry. Rejection of urea occurred in the 1960's and was based on demonstrations of ammonia volatilisation in dry and alkaline soil conditions and on poorer agronomic performance (Cooke, 1975; Chaney & Paulsen, 1988). The main recent change has been the increased but still minor use of prilled urea, stimulated by low prices of imported urea, a re-assessment of its efficacy (Archer & Lloyd, 1992) and the development of pneumatic spreaders or on-farm liquid systems which can cope with the variable physical state of some supplies.

1.3 The availability of prilled ammonium nitrate of good quality and conveniently packed ensures its widespread use. It can be satisfactorily spread with cheap machinery. Although heavier per load than urea this is not a major disadvantage. Some enterprises find liquids more convenient because pesticides can be incorporated and spreading can be more uniform.

Except on soils with free lime, physiological considerations have little impact on the result since all forms of nitrogen are currently understood to be or become rapidly available for both uptake and loss processes. Recent experiments have however shown less or later lodging and a slightly smaller concentration of nitrogen in grain where solid urea has been used rather than solid ammonium nitrate.

1.4 The decision has a direct effect of £10 to 40 per ha on growers' costs. Occasionally yield can be reduced by up to 0.5 t/ha from using urea on soils with chalk or limestone in dry conditions, but cost savings may counteract this. Effects on grain quality are not normally significant.

1.5 Recent findings of differences in growth (observed as lodging) and grain quality after use of urea and ammonium nitrate indicate that soil transitions or plant uptake are not as similar as is currently supposed. Further investigations on crop uptake are being undertaken by ADAS Cambridge (H-GCA funded) on malting barley.

Recent work indicates smaller N residues after urea than ammonium nitrate. The incomplete recovery of fertiliser nitrogen and the mobility of unused residues represent a major financial loss to the producer and an environmental problem to the industry. Research should be supported on forms and techniques of fertiliser application which could minimise interaction with soil biomass and maximise direct crop uptake. In this light tests should be made of:

- natural and artificial inhibition of biomass activity
- form of N applications to soil
- foliar versus soil applications
- formulations of foliar N applications
- application techniques of foliar N

2. Autumn Nitrogen

2.1 None

2.2 Use of nitrogen at or after sowing in the autumn has decreased from about three quarters of fields in 1983-4 to about one third of fields in 1987-8. Slightly more is used for winter barley than winter wheat. It is largely applied in compound form with phosphate and potash. Use has decreased because of:

- greater flexibility from increased use of 'straights'
- field trials showing immobilisation, low recovery and lack of response

- earlier drilling and better appreciation of soil N release in autumn
- less direct drilling which can lead to inadequate mineralisation of soil nitrogen
- greater use of nitrogen in spring causing larger soil N residues in autumn
- publicity on losses of nitrate nitrogen by leaching and run off.

2.3 Autumn nitrogen may be used purely because its exclusion from the fertiliser provides no saving in cost or inconvenience.

When used it is intended to supplement soil supplies which may be low because of:

- depletion by the previous crop
- immobilisation by incorporated straw, chaff or stubble
- inadequate disturbance by cultivation or to stimulate leaf, tiller or root expansion which may have been inhibited by late or deep drilling
- inadequate establishment
- slug or wheat bulb fly attack

When used, the average amount was 25 kg/ha N on winter wheat in 1987-8.

2.4 The cost of autumn N is small and the effect on yield is normally undetectable (average + 0.05 t/ha for 84 trials on winter barley). The decision principally affects the image of the industry in the eyes of a public which seeks to see responsible management of the farmed environment.

2.5 None

3. Total amount of spring and summer fertiliser nitrogen

3.1 From 60 to 300 kg/ha. Averages for England and Wales in 1985-8 were about 190 kg/ha for winter wheat, 150 kg/ha for winter barley and 100 kg/ha for spring barley.

3.2 Over the decade to 1985 average nitrogen use increased by about 100 kg/ha for winter wheat, 60 kg/ha for winter barley and 30 kg/ha for spring barley (Fig. 1). Increased use was stimulated by a combination of factors:

- increasing profit margins, leading to reduced pressure on control of variable costs.

- development of varieties and techniques to counteract consequences of over-use of nitrogen (through growth regulators to control lodging and fungicides to control foliar diseases).

- an increasing tendency to associate low yields with low nitrogen usage.
- (for wheat) the increasing dependence of marketability on protein concentration of grain.

The increases were smaller for barleys than for wheat because profit margins were smaller, lodging control was not so successful and marketability depended on low grain nitrogen concentrations.

Nitrogen use has been more stable recently, principally because profit margins have been smaller. The reduced use of autumn nitrogen has probably been counteracted (for wheat) by increased use of late nitrogen to increase grain protein.

3.3 The decision on amount of nitrogen is based principally on past practices and performance; dependence on current observations is minimal. In addition to recent profits from the enterprise adjustments to previous nitrogen usage are based on:

- changes in yield expectation according to performance in recent years and occasionally modified by the appearance of the crop in early spring.

  For wheat, ADAS and fertiliser manufacturers advise adjustments of about 25 kg/ha N per tonne of difference in yield expectation. Such adjustments are less explicit for other cereals principally because of their propensity to lodge where more than 100 (for oats and rye) or 150 (for barley) kg/ha N is applied.

- maximising the chances of the crop achieving its intended market. Having identified the probable market when the variety was chosen there follows a commitment to maximise the chances of achieving that market by adjusting by 30-40 kg/ha the nitrogen amount if acceptance depends on grain nitrogen concentration. Nitrogen is increased for breadmaking markets and decreased for malting. Increases for breadmaking have a questionable effect on marketability and are now always advised.

- differences in the expected supply of soil nitrogen. Expectations are normally assessed according to previous crop, previous use of fertilisers and manures, and likely retention of residues according to texture and depth of soil. Adjustments made in practice after rape, potatoes or legumes average are less than 10 kg/ha N whereas adjustments advised range from 25 to 100 kg/ha N. Where residues are expected to be large, confirmation can be obtained through soil analysis for ammonium and nitrate nitrogen.

3.4 Grain yields are commonly doubled by use of fertiliser nitrogen. However, over a series of seasons and similar sites, adjustments of 30 or 40 kg/ha from a best average amount decreases average profit by less than £10 per hectare because the marginal return changes little in the region of the optimum. The decisions of importance are thus whether nitrogen should be applied, and whether a major departure from the average optimum should be anticipated.

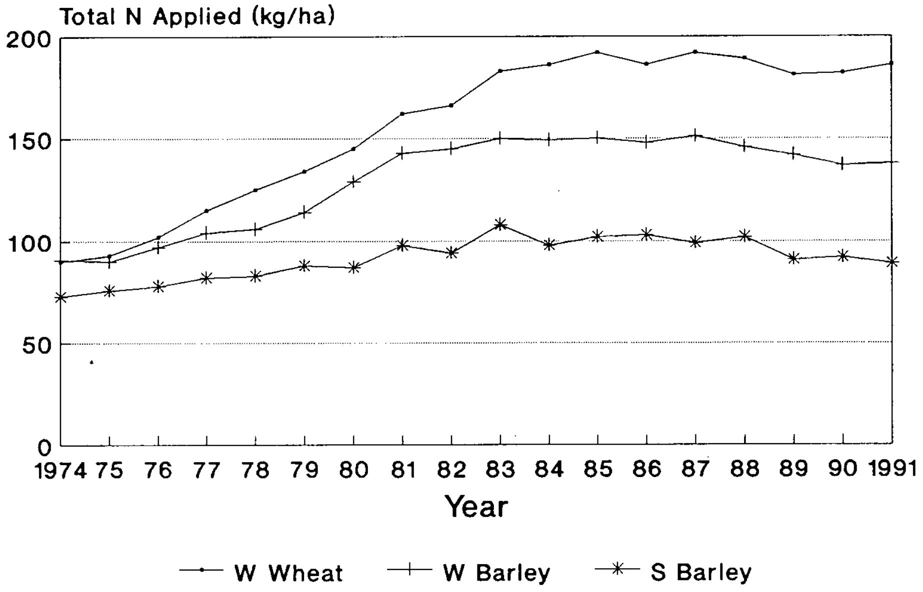

Figure 1. *Average applications of nitrogen to cereal crops in England & Wales.*

3.5 A considerable proportion of variation in grain yield is associated with events after the decision is made. However the component of the variation which has been determined beforehand (due to site, husbandry and weather) appears sufficiently important for inclusion in the assessment of yield expectation and there is a need for characterisation of criteria for better assessment of yield potential at this stage. Initial work should exploit existing data such as the Wheat (Avalon) Growth Study conducted by ADAS and AFRC at ten sites from 1982 to 1984. Future experimentation requires the monitoring of candidate criteria to be coordinated across seasons with sites chosen with regard to soil and climate.

The association between yield expectation and crop nitrogen requirement is weak (Bloom *et al.*, 1988) apparently because of variation between sites in crop recovery of nitrogen (both applied and residual) and in crop nitrogen concentration. Most of the variation is unexplained but as variation within one site (in one season) is minimal and variation between sites is large there are good prospects of some explanation through structured experimentation. Observations should concentrate on sub-ground processes such as root proliferation, the influence of root exudation on immobilisation of N, and changes in N content of soil biomass. Experiments should exploit known effects such as the better recovery of residual nitrogen by spring than autumn sown crops e.g. barley (and sugar beet) and the less concentrated nitrogen in cereal crops after a break crop than after a cereal (Vaidyanathan *et al.*, 1987).

4. <u>The number of nitrogen applications (between which the total amount is divided)</u>

4.1 Two, but three for wheat grown for breadmaking.

4.2 The advent of divided N applications in the 1970's, preceded extensive verification in field trials; decisions were initially made on the basis of principles which represented differing degrees of appreciation of functional processes, including physiology of the plant. Few of the processes were (or are) well quantified so the decision was a complex and uncertain value-judgement. The processes are as follows:

- Growth was sometimes seen as a compound process (Watson) in which early investments gave the best return. Growth was later seen as energy conversion from intercepted radiation to dry matter (Montieth) such that improved interception would translate to improved dry matter accumulation.

- Increased uptake of nitrogen was known to stimulate organ expansion. Early effects have both positive and adverse repercussions:

  - Larger leaves intercept more light.

  - Larger, softer leaves are more prone to infection.

  - Larger root systems provide more assured supplies and help to overcome root diseases such as take-all.

- Longer, softer internodes and root axes are subsequently weaker.

As the amount of spring-applied nitrogen has increased so has the tendency to divide it between two or more applications. Divided applications have been encouraged by:

- yield advantages demonstrated by experiment
- earlier drilling causing earlier depletion of residual nitrogen in the soil, observed as yellower crops.
- greater appreciation of a need to minimise risk of N losses by matching N supply to the progress of growth.

When wheat is being grown for breadmaking it has been the practice for many years to apply a portion of the total amount late, during stem extension or grain filling, because of the greater effect of grain N concentration.

Conversely, when barley is being grown for malting a need to minimise the effect of grain N concentration often encourages the use of a single early application (during March).

4.3 The decision depends mainly on an assessment of levels of residual nitrogen, such that larger levels are exhausted later and reduce the total amount to be applied. It is uncommon for small (less than 100 kg/ha N) total amounts to be divided.

Conversely, large amounts, particularly where labour and spreaders are available, are commonly applied in three or four applications. This minimises the risk of restricted uptake of a large application by delay until after the onset of dry conditions.

4.4 Divided nitrogen applications incur little extra cost and on average cause a small yield advantage of 0.2 t/ha (range: -0.4 to +0.8 t/ha).

4.5 Improved decisions are unlikely without a better assessment of the primary causes of variation. Emphasis should be given to soil processes. Each application significantly alters the environment in which crop roots and soil organisms compete for nitrogen. Frequent applications are likely to cause a balance which contrasts with that caused by few and thus large applications. An understanding of this balance offers a prospect of improving fertiliser recovery and crop response by exploiting the industry's versatility in making nitrogen applications in any of many different ways.

Current understanding of responses in shoot growth is more adequate. However, for production of malting barley, there is evidence which should be checked that only part rather than all the total amount need be applied early in order to give a small nitrogen concentration in the grain.

5. Amount and timing of early spring nitrogen

5.1 40 kg/ha N applied in late February or early March.

5.2 The quantity and timing of nitrogen applied at this stage was rarely varied for anything other than arbitrary or pragmatic reasons.

The much publicised philosophy of timing applications at a particular stage of development (in this case the double-ridge stage, Kirby & Appleyard) has not shown a consistent benefit. The philosophy purported to be based on physiological principles but was never properly documented and superficial publicity has result in not inconsiderable misunderstanding of the relative importance of factors affecting decisions relating to applications of early spring nitrogen.

Amounts of nitrogen taken up by crops before the next application are not large enough to suggest a need for greater than 40 kg/ha early amount. Large early amounts tend to be associated with lodging.

Local variations in the amount of early spring nitrogen have become established. For example on Keuper Marl Soils in Nottinghamshire it is very small or omitted and on heavy silt soils around the Wash about 60 kg/ha is used.

Adoption of a relatively standard early amount in the UK contrasts with practice in Denmark, Germany, Holland and Belgium where alterations in the total nitrogen amount are normally achieved through adjustments in this first application.

5.3 As with most decisions in nutrition of crops, information must be judged with the intention of optimising the balance between soil supply and crop demand by making an assessment of soil supply (see 3.3) and the amount of nitrogen the crop needs to access before the next intended application, taking into account:

- Extent of root exploration
- Amount of leaf tissue present
- Projected temperatures and light environment

- Intended nitrogen concentration in the crop at harvest (e.g. malting quality of grain)

The timing of the application is intended to pre-empt any restriction of growth but again is principally governed by pragmatic factors such as:

- Whether good ground conditions will allow tractors to travel

- Whether winds allow accurate spreading

But should also take into account patterns of rainfall and its affect on risks of:

- Leaching of nitrate from the rooted zone.

- Waterlogging and possible denitrification.

- Restricted mobility of nitrate in soil due to dryness and therefore reduced crop uptake.

5.4 Differences in timing or amount of early spring nitrogen rarely cause detectable differences (greater than 0.1 t/ha) in yield or grain nitrogen concentration except where they are the crucial cause of lodging.

Research into decisions which only cause marginal and inconsistent effects is difficult to justify in economic terms and must be sufficiently comprehensive to provide a detailed description of interacting processes.

Research into plant analysis as a basis for decisions has not lead to its acceptance in practice (cf. Darby *et al.*, 1986; Sylvester-Bradley *et al.*, 1984) on account of cost or inconvenience and the rapid onto genetic drift in target values.

5.5 The effect of timing and amount of early nitrogen on immobilisation is virtually unknown and should be more closely studied (see 4.5).

Adjustments in early nitrogen applications can change the propensity of the crop to lodge. Points of structural weakening should be identified given the uncertainty on the origin of lodging.

Controversy remains as to whether crops with advanced or retarded development should be top-dressed first. Effects on tillering, DM and nitrogen accumulation and soil N content in the phase before the main application could be measured more extensively to allow an integrated basis for decisions.

6. Timing of the principle application

6.1 The start of stem extension

6.2 Timing of the main application is similar for all cereal crops and has not changed for many years. Nitrogen is seen to be needed in proportion to the pattern of growth and growth is seen to accelerate as stem extension starts and as radiation levels increase. Deficiency effects on not only the colour of leaves but on growth and tiller survival become readily apparent soon after this stage. The stage also coincides with increased risk of a dry soil surface which can delay or reduce the uptake of applied N.

Barley crops intended for malting normally receive the main application during March even if stem extension has not started in order to minimise the effect on grain N concentrations.

6.3 The start of stem extension varies according to date of sowing, overwinter and early spring temperatures, and variety. However, dates of application are only loosely linked to these through stage of the crop because:

- recognition of the stage varies
- other operations, such as establishment of spring crops and application of herbicides and fungicides, may take priority
- wet soil, rain or wind prevent spreading
- reducing the risk of a dry soil surface overrides the policy of linking application to crop stage. This is most important for cereals sown in late spring.

6.4 There is little direct evidence of how timing alters the effect of the main application. Mistiming is unlikely to have an effect larger than 0.2 t/ha except where dryness delays uptake.

6.5 In the UK, although emphasis on the start of stem extension appears to be soundly based in principle, evidence for this policy is largely circumstantial. There has been no concerted attempt to disentangle effects of the normally concurrent changes in solar radiation, soil moisture, canopy expansion and root growth.

On the Continent the main application may not be made when stem extension starts; in Germany where growth accelerates more rapidly in spring and summer rainfall is more reliable, larger applications are often made both in early spring and before grain filling.

An examination of restrictions on timing the main application in the UK would be worthwhile because there is a prospect of amounts applied later having equal efficacy and thus allowing a closer match to crop potential.

7. Amount of nitrogen applied late (to wheat grown for breadmaking)

7.1 30 kg/ha

7.2 There has been no trend in the inherent protein concentrations of the successive breadmaking varieties grown over recent years and, although grain yields have increased considerably, the increase in overall use of nitrogen has at least compensated for this. Thus, there has been no detectable trend in grain protein concentrations, and the incentive to boost concentrations with a late application of nitrogen has not changed.

7.3 The choice of a breadmaking variety is commonly understood to commit a grower to use of late nitrogen. This reasoning is often flawed because, although late nitrogen almost always increases grain protein concentration, this does not ensure acceptance of the grain for breadmaking at a premium over the feed price. Irrespective of enhanced level of protein, the grain may be rejected through high moisture or impurities, low Hagberg Falling Number or specific weight. Furthermore, the sale is usually based on a threshold protein concentration. Thus the sale may fail because the threshold is not met even with late nitrogen or the application may be unnecessary because the threshold would have been met even in its absence. Lastly, any premium gained may not be adequate to cover the cost of the late nitrogen application.

Although astute decisions on the quantity of late nitrogen should consider its chances of affecting the sale price, in practice the amount applied is decided by relating its cost to the expected return in premium payment. The amount used can be partly compensated by a small increase in grain yield.

7.4 Use of late nitrogen normally has a small and negative influence on returns. Occasionally, where a sale is effected by the decision, a large return will accrue. At present these instances cannot be predicted.

7.5 Use of late nitrogen could be more effective if the chance of affecting price could be predicted. There is little prospect of predicting Hagberg Falling Number or specific weight before the decision must be made but it is possible that crop analysis would assist the prediction of grain protein levels.

Development of techniques for grain analysis at point of sale for the proteins of particular value in breadmaking could improve the commercial framework for this decision. H-GCA currently funds research into amounts of late nitrogen and their effects on grain proteins.

8. Form, method and timing of late nitrogen applications (to wheat grown for breadmaking)

8.1 Prilled ammonium nitrate, broadcast during May.

8.2 In practice, where late N is applied, a simple choice is made between prilled ammonium nitrate applied a few weeks after the main application and a solution of urea sprayed during grain filling. Use of urea sprays has increased in recent years due to increased availability of cheap urea, increased marketing by manufacturers, and continuing interest generated by experimentation. However, sprays are still only used by a minority of producers.

8.3 Application of prills is more convenient than sprays, for which a specific purchase must normally be made. Early applications are perceived to have a good prospect of increasing grain yield as well as protein concentration if uptake is not delayed by soil dryness. Urea sprays are seen to scorch leaves but are perceived to cause large increases in grain protein concentration. Yield reductions have been associated with scorch, but conversely manufacturers claim yield enhancement from urea sprays. Urea sprays can have fungicidal effects.

Efficacy of urea sprays has been questioned by the bakers who have been unable to associate increases in grain N with improvements in baking performance of the flour. This has not yet affected returns to growers.

8.4 Costs of both methods of application are similar. Given the infrequency of benefits from use of late N (see 7.4) the choice of application method is seldom important to the grower. However, sprayed urea is likely to leave a smaller soil N residue than prilled ammonium nitrate.

8.5 Although recent research has shown that choice of method of applying late N has little immediately commercial significance, further research has the prospect of reducing N residues and thus leaching risk. There is thus scope for a programme to:

- determine the cause of scorch by urea sprays
- develop formulations and techniques to maximise retention of urea sprays by cereal canopies
- establish the metabolic pathway whereby urea is assimilated by leaves
- establish translocation patterns for urea N assimilated by leaves
- devise practices which maximise recovery of sprayed urea N by canopies and minimise soil residues.

H-GCA currently funds research on timing of urea sprays and their effects on grain proteins.

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COMPARISON OF AMMONIUM NITRATE AND UREA SOLID NITROGEN TOP DRESSING FOR WINTER CEREALS

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SUMMARY

During 1982-1985, trials was carried out on 32 sites in England and Wales to compare ammonium nitrate and urea as solid nitrogen top dressings for winter cereals.

The relative effectiveness of the two fertilisers was compared on the basis of the mean yields from all the nitrogen rates tested. Only at 5 sites was there a significant difference between the two fertilisers - with three showing an advantage to ammonium nitrate and two to urea. Overall there was no significant difference between the fertilisers for the 32 sites. However, for the 14 sites which were on shallow chalk soils, there was a significant yield benefit from the use of ammonium nitrate with a mean yield loss of 0.09 t/ha (1.23 %) from the use of urea. This compared with an average non-significant yield increase of 0.01 t/ha (0.14 %) with urea on the non-chalk sites.

Grain nitrogen data showed an overall slight decrease of 0.05 % from urea applications. The decrease from urea was significant at 7 sites. Only at 4 sites was there an increase (although non-significant) in grain nitrogen following urea application.

For the 1983-1985 trials, the main nitrogen dressing was applied either as a single dressing at GS30/31 or as a split dressing (half at GS30/31 and half about two weeks later). At no site was there a significant difference between single and split urea applications.

INTRODUCTION

While ammonium nitrate dominates the straight nitrogen fertiliser market in the UK, there has been increasing farmer interest in the use of urea during the 1980s. Previous work carried out in the UK and reviewed by Tomlinson (1970) looked at the comparison of urea and ammonium nitrate as nitrogen fertiliser sources for a very wide range of crops. Chaney and Paulson (1988) have recently reviewed a large number of field experiments carried out over the last 30 years in England and Wales. The general conclusion regarding the comparison of these two sources of nitrogen fertiliser for the top dressing of winter cereals under UK conditions has always favoured ammonium nitrate, but often by only a small margin. Very few experimental comparisons have been carried out on winter cereals producing current levels of yield.

This series of experiments carried out in England and Wales between 1982 and 1985 was initiated in order to try and define more precisely under what site/soil conditions and by how much the yield penalty resulting from the use of urea, compared to ammonium nitrate, would occur. This then enables an economic decision to be taken by the farmer regarding the best choice of nitrogen fertiliser for a particular field producing winter cereals. Thirty-two field experimental comparisons of the two nitrogen sources are presented, carried out predominantly on winter wheat but with a few winter barley sites included.

The paper interprets these experimental findings and discusses the economics of fertiliser choice.

MATERIALS AND METHODS

This series of experiments was carried out on commercial field crops of winter wheat and winter barley in England and Wales between harvest years 1982 and 1985. Each crop received normal farm inputs of other nutrients and weed, pest and disease control agrochemicals as appropriate.

The sites were located on a biased range of soil types to include a number of chalk soil types - mainly Upton and Andover Series. This strategy was adopted as it was anticipated that soil type was most likely to show any yield disadvantage of urea compared to ammonium nitrate. Many workers have shown increased risk of volatile ammonia loss when top dressing urea on chalk soils. Nearly all sites followed a previous cereal. This rotational position was chosen to ensure substantial site yield response to nitrogen fertiliser.

TABLE 1: SITE DETAILS

Site No.	Name	Texture	Soil Series	pH	OM%	$CaCO_3$%	(1) N Index	(2) Variety
1982:								
A1	High Mowthorpe	ZL	Andover	7.8	3.8	1.9	0	WW Aquila
A2	Boxworth	CL	Hanslope	8.1	3.9	15	0	WW Hustler
A3	Red Rice	ZL	Andover	8.1	4.8	7.5	0	WW Bounty
A4	Black Peak	ZCL	Burwell	7.9	3.2	42	0	WW Avalon
1983:								
B1	Easton	ZL	Andover	8.2	5.1	2.6	0	WW Hustler
B2	Micheldever	ZL	Andover	8.0	3.9	4.9	0	WW Avalon
B3	Stansted	ZCL	Hanslope	8.2	2.4	13	0	WW Norman
B4	Sladesbridge	SZL	Denbigh	7.5	6.5	4	0	WW Rapier
B5	Boscar Grange	LFS	Everingham	7.1	1.3	0	0	WB Igri
B6	High Mowthorpe	ZCL	Andover	8.1	4.2	7.6	0	WW (Blend)
B7	Cotswold CC	ZCL	Evesham	7.3	4.6	5	0	WW Norman
B8	Daltons	ZL	Upton	8.6	4.9	57	0	WW Prince
B9	Boxworth	CL	Hanslope	8.1	3.9	15	0	WW ?
B10	Low Caythorpe	ZCL	Coombe	8.6	3.8	3.4	0	WW Avalon
B11	Foston	CL	Romney	6.8	3.9	0	0	WW Avalon
1984:								
C1	Aldwark	LS	Kexby	6.3	1.4	0.1	0	WB Igri
C2	Thornton Hall	CL	Brickfield	6.4	3.9	0.2	0	WB Mix
C3	High Mowthorpe	ZL	Andover	7.8	6.2	4.9	0	WW Aquila
C4	Bubwith	SL	Kexby	6.9	1.4	0	1	WW Brigand
C5	Garton	ZL	Andover	8.1	4.1	10.6	0	WW Longbow
C6	Fordon	ZL	Andover	7.6	4.9	1.3	0	WW Prince
C7	Overton	ZL	Andover	7.8	5.1	4.7	0	WW Rapier
C8	Red Rice	ZL	Andover	7.5	3.3	12.9	0	WW Rapier
C9	Cotswold CC	ZCL	Sherborne	8.0	6.0	16.3	1	WW Longbow
C10	Daltons	ZL	Upton	7.9	6.6	30.6	0	WW Avalon
C11	Boxworth	CL	Hanslope	8.3	2.9	11.5	0	WW Longbow
C12	Langston	SZL	Denbigh	6.4	4.6	0.1	0	WB Igri
C13	Llanfaelog	SL	East Keswick	6.4	5.1	0	0	WW Norman
1985:								
D1	High Mowthorpe	ZCL	Andover	7.1	6.0	4.4	0	WB Igri
D2	Ashcombe	CL	Crediton	6.7	3.8	0.2	0	WB Panda
D3	Egmere	SL	Berrow Ass'n	7.9	1.1	0	0	WW Longbow
D4	Cotswold CC	ZCL	Sherborne	8.2	5.1	16	0	WW Avalon

(1) N Index 0 - following cereal
N Index 1 - following one year arable breakcrop

(2) WW - Winter wheat; WB - Winter barley

The experimental treatments were applied at two timings. In 1982, the two materials were applied split with 40 kg/ha N early in late February/early March or at a single time of application at GS 30/31. The split treatments had the remainder of their nitrogen applied at GS 30/31. In the following years, 1983-85, all treatments received 40 kg/ha N early. The main applications in these years were split or single timed. The single timing was applied at GS 30/31 while the split timing was applied half at GS30/31 and half around 14 days later. These treatments of urea and ammonium nitrate were applied to each site at the following rates:-

1982	80, 120, 160, 200, 240, 280 kg/ha N
1983-85	100, 140, 180, 220, 260, 300 kg/ha N

All sites included a nil nitrogen control treatment. All treatments were applied by hand as prilled urea (46% N) and ammonium nitrate (34.5% N).

The experimental design was two replicates of a randomised block at each site, with two controls included in each replicate. Plots were harvested by combine harvester and a minimum of 50 m^2 was harvested. Grain yields were expressed at 85% dry matter. Grain nitrogen content was measured by near infra-red spectroscopy and expressed as percentage nitrogen in the grain dry matter (weight basis).

RESULTS

The details of the sites chosen for these experiments are given in Table 1. Sites were located throughout the cereal-growing areas of England and Wales. The texture given in the table is the surface texture as defined by the ADAS/SSLRC system. The pH figures are for a soil water suspension (1:2.5 ratio of soil to water). The organic matter and calcium analyses are as described in ADAS 'Methods of Analysis', Reference Book 427 (1986). The nitrogen Index is taken from the nitrogen recommendation system used by ADAS as described in Fertiliser Recommendations, Reference Book 209 (1988).

TABLE 2: EFFECT OF CHOICE OF NITROGEN SOURCE ON MEAN YIELD (t/ha - 85% DM)

Site	AN Yield	Urea Yield	AN - U Yield	$\frac{AN - U}{AN}$ %	~ LSD P = 0.05
A1	4.82	4.58	+ 0.24	+ 4.98	0.25
A2	6.58	6.52	+ 0.06	+ 0.91	0.27
A3	5.45	5.49	- 0.04	- 0.73	0.23
A4	5.78	5.80	- 0.02	- 0.35	0.08
B1	8.88	8.91	- 0.03	- 0.34	0.10
B2	7.03	7.01	+ 0.02	+ 0.29	0.23
B3	7.80	7.84	- 0.04	- 0.51	0.17
B4	5.12	5.06	+ 0.06	+ 1.17	0.40
B5	5.93	6.03	- 0.10	- 1.69	0.15
B6	8.25	8.08	+ 0.17	+ 2.06	0.17*
B7	8.41	8.49	- 0.08	- 0.95	0.21
B8	7.51	7.35	+ 0.16	+ 2.13	0.13*
B9	8.20	8.30	- 0.10	- 1.22	0.09*
B10	8.46	8.39	+ 0.07	+ 0.83	0.17
B11	6.48	6.39	+ 0.09	+ 1.39	0.20
C1	4.42	4.28	+ 0.14	+ 3.17	0.17
C2	10.30	10.22	+ 0.08	+ 0.78	0.20
C3	8.56	8.56	0	0	0.23
C4	7.90	7.89	+ 0.01	+ 0.13	0.15
C5	10.63	10.77	- 0.14	- 1.32	0.18
C6	6.46	6.47	- 0.01	- 0.16	0.23
C7	6.51	6.14	+ 0.37	+ 5.68	0.20*
C8	5.66	5.36	+ 0.30	+ 5.30	0.33
C9	7.99	8.05	- 0.06	- 0.75	0.27
C10	7.84	7.68	+ 0.16	+ 2.04	0.16
C11	9.47	9.45	+ 0.02	+ 0.21	0.20
C12	7.91	7.78	+ 0.13	+ 1.64	0.16
C13	6.88	7.11	- 0.23	- 3.34	0.23*
D1	6.32	6.26	+ 0.06	+ 0.95	0.17
D2	7.52	7.80	- 0.28	- 3.72	0.38
D3	7.57	7.38	+ 0.19	- 2.51	0.21
D4	5.17	5.28	- 0.11	- 2.13	0.21

* Significant difference (p = 0.05)

MEAN		AN Yield	Urea Yield	AN-U Yield	$\frac{AN-U\%}{AN}$	LSD P=0.05
All sites	(32)	7.27	7.24	+0.03	+0.41	0.047
Chalk sites	(14)	7.31	7.22	+0.09	+1.23	0.054
Non-chalk sites	(18)	7.24	7.25	-0.01	-0.14	0.013

~ Least significant difference when comparing AN yield with Urea yield

TABLE 3: EFFECT OF NITROGEN SOURCE ON GRAIN NITROGEN CONTENT (% N - DM basis)

Site	AN	U	AN - U	LSD (p = 0.05)
A1	2.54	2.49	+ 0.05	0.23
A3	2.01	1.99	+ 0.02	0.05
B1	1.86	1.80	+ 0.06	0.04*
B2	1.95	1.91	+ 0.04	0.05
B3	1.91	1.92	- 0.01	0.05
B4	2.10	2.00	+ 0.10	0.06
B5	2.29	2.04	+ 0.25	0.11*
B6	1.87	1.84	+ 0.03	0.06
B7	1.90	1.90	0	0.10
B8	1.99	1.94	+ 0.05	0.05*
B9	2.13	2.13	0	0.06
C1	2.52	2.44	+ 0.08	0.04*
C2	2.15	2.09	+ 0.06	0.09
C3	1.98	1.91	+ 0.07	0.07
C4	2.31	2.30	+ 0.01	-
C5	1.77	1.73	+ 0.04	-
C6	2.09	2.01	+ 0.08	-
C7	2.09	2.10	- 0.01	0.04
C8	2.07	2.09	- 0.02	0.05
C9	2.06	2.03	+ 0.03	0.05
C10	2.25	2.15	+ 0.10	0.04*
C11	1.86	1.88	- 0.02	0.05
C12	2.08	2.06	+ 0.02	0.09
C13	2.06	2.06	0	0.03
D1	1.91	1.83	+ 0.08	0.04*
D2	2.08	2.08	0	0.04
D3	1.96	1.93	+ 0.03	0.04
D4	1.79	1.72	+ 0.07	0.04*
MEAN	2.06	2.01	+ 0.05	

* Significant difference (P=0.05)

TABLE 4 EFFECT OF SINGLE AND SPLIT AMMONIUM NITRATE AND UREA APPLICATIONS ON GRAIN YIELD

Site No.	AN Single	Urea Single	AN Split	Urea Split	LSD Timing	LSD Timing x Source
B 1	8.87	8.94	8.89	8.88	0.10	0.14
2	6.98	7.09	7.07	6.94	0.23	0.33
3	7.80	7.87	7.80	7.81	0.17	0.25
4	5.10	5.18	5.15	4.93	0.40	0.56
5	5.84	5.90	6.02	6.16	0.15*	0.21
6	8.45	8.19	8.04	7.77	0.16*	0.23
7	8.50	8.41	8.32	8.56	0.21	0.29
8	7.51	7.24	7.51	7.46	0.13	0.18
9	8.25	8.25	8.14	8.34	0.09	0.13*
10	8.52	8.46	8.40	8.31	0.17	0.24
11	6.47	6.47	6.49	6.30	0.20	0.28
C 1	4.59	4.30	4.26	4.26	0.17*	0.24
2	10.36	10.11	10.24	10.33	0.20	0.28
3	8.57	8.69	8.54	8.44	0.23	0.33
4	7.87	7.87	7.92	7.92	0.15	0.21
5	10.54	10.65	10.73	10.88	0.18*	0.25
6	6.46	6.47	6.47	6.47	0.23	0.32
7	6.45	6.06	6.56	6.21	0.20	0.29
8	5.59	5.39	5.74	5.34	0.33	0.47
9	8.12	8.14	7.86	7.96	0.27	0.38
10	7.97	7.59	7.71	7.77	0.16	0.23*
11	9.64	9.46	9.29	9.43	0.20	0.28
12	7.93	7.74	7.90	7.81	0.16	0.23
13	6.90	7.13	6.86	7.10	0.23	0.33
D 1	6.22	6.24	6.43	6.28	0.17	0.23
2	7.50	7.74	7.53	7.85	0.38	0.54
3	7.69	7.46	7.45	7.30	0.21	0.30
4	5.19	5.32	5.15	5.24	0.21	0.30

LSD Timing compares means of AN single and U single with means of AN split and U split

LSD Timing x source compares between the four (fertiliser type x timing) values for each site

* Significant difference (P=0.05)

The mean grain yields for the two sources of nitrogen are tabulated for each experimental site in Table 2. These means exclude the control treatments. The third column gives the difference in yield due to choice of nitrogen source, which is expressed in column 4 as a percentage of the ammonium nitrate yield. The LSD in column 5 relates to the comparison of the mean yields in columns 1 and 2. Five sites show a significant yield difference between the materials at the 0.05% level. Three favour ammonium nitrate, and two favour urea.

Overall mean data for the 32 sites shows a small advantage of 0.41% in favour of ammonium nitrate compared to urea. If the chalk and non-chalk sites are split into two groups, the 14 chalk sites have an overall average of 1.23% yield loss with urea against a yield benefit to urea of + 0.14% for the 18 non-chalk soil type sites.

The grain nitrogen content data (Table 3) shows that the majority of sites have produced a slightly lower grain nitrogen content where urea has been used compared to ammonium nitrate. The mean of 28 sites where grain nitrogen content data is available shows an overall reduction in content of 0.05% (dry matter basis). This is equivalent to approximately 0.25% protein (86% dry matter basis). This effect was very consistent over all sites; only 4 sites gave an increase in grain nitrogen content where urea had been used.

Examination of the effect of splitting both urea and ammonium nitrate main topdressings on the 28 sites in 1983-1985 showed only occasional significant differences (Table 4). Split applications received half their nitrogen approximately 14 days after the first GS 30/31 application time.

When comparing single against split main dressings meaned for the 2 materials, two sites showed a significant yield increase and two a significant decrease. When comparing the individual means for the four different timing and fertiliser combinations, the only significant difference were at sites B9 and C10. They both showed a significant difference between single and split ammonium nitrate in favour of the single application, but there was no significant yield difference between single and split urea for either site.

DISCUSSION

Yield Comparison

After attempting a number of presentations of the yield data, it was decided that the comparison of means of all the nitrogen rates tested was the most appropriate. Selection of the means from the nitrogen levels either side of the ADAS recommended rate for each site was rejected because these values did not necessarily agree with the individual site economic optima. In practice this approach gave very similar yield differences but with a higher LSD as only part of the data was being used.

Attempts to fit curves to the data were also rejected as the small differences between treatments were determined by the choice of curve selected.

By meaning over a range of nitrogen rates spanning the optimum for each site, but with more rates below than above, it is suggested that a fair and realistic comparison of the two materials has been made on which practical inferences can be based.

Economics of Material Choice

Assuming equal cost per kg N for each material, ammonium nitrate is favoured overall and particularly on chalk soils.

Using a grain price of £100/t and an ammonium nitrate (34.5% N) price of £115/t, the following break-even prices for urea (46% N) can be calculated assuming a 7.5 t/ha crop receiving 200 kg/ha N.

YIELD PENALTY AN-U	UREA BREAK-EVEN PRICE - £/tonne
0%	£153
1%	£135
2%	£118
3%	£101
5%	£67

This assessment assumes that the economic optimum amount of nitrogen needed is the same for each material in kg/ha N. This will only apply for small differences in price per kg N between the two materials. If one is more than 10% cheaper than the other per kg N, the optimum N amount of the cheaper fertiliser and the yield at the optimum will be increased, giving a further small economic advantage to the cheaper source.

This assessment also assumes that the response curves for the two materials are parallel. If the yield penalty from using urea can be economically reduced by increasing the amount of urea applied, the economic benefit would again shift slightly in favour of urea.

However, examination of the data from those sites giving a significant difference ($p = 0.05$) between the mean yields produced by the two materials suggests that the difference between them is similar at both the higher and lower rates tested. This suggests that the yield gap cannot be economically reduced by applying more of the poorer performance material. Furthermore, it does not support the view that the main mechanism resulting in the poorer performance of urea is volatile ammonia loss. If this mechanism was responsible, a stronger indication that the difference between the yields from the two materials are reduced at higher nitrogen rates would be expected.

Grain Nitrogen Content

Although the data shows a consistent small effect of urea producing a lower grain nitrogen content than ammonium nitrate, it is unlikely to be an overriding factor in the farm choice of nitrogen source. For milling wheat, a 0.25% protein (86% DM) advantage in favour of ammonium nitrate will be one of the factors that should be taken into account. For malting barley production, the 0.05% N (DM basis) advantage in favour of urea is perhaps more likely to be considered economically important, especially where the premium is on a nitrogen content sliding scale. The reason for this effect on grain nitrogen content is unclear.

Splitting the Main Dressing

At most sites there was no advantage or disadvantage from splitting the main dressing of either ammonium nitrate or urea compared to a single GS 30/31 application. Two sites showed single ammonium nitrate to be significantly better than split ammonium nitrate but at no site was split urea significantly better than a single dressing of urea.

If ammonia volatilisation loss had been a major factor in determining yield losses with urea, one might have expected at some sites split urea dressings to have given higher yields than single applications.

ACKNOWLEDGEMENTS

These experiments were carried out by numerous ADAS colleagues. The preparation of this paper was funded by the HGCA Cereal R & D levy.

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NITROGEN RESIDUES FROM PEAS AND BEANS AND THE RESPONSE OF THE FOLLOWING CEREAL TO APPLIED NITROGEN.

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SUMMARY

A series of about 30 comparisons over three years measured the nitrogen available to winter wheat after crops of peas, field beans and cereals. Peas left more residual mineral nitrogen in the soil than beans when measured in autumn and beans left more than cereals, but bean residues apparently continued to mineralise over winter, so that differences between peas and beans in soil mineral N, total crop N, and responses to applied nitrogen were not significant in the spring or at harvest. Responses to applied nitrogen were larger after cereals than after legumes; on average, optimum amounts of applied nitrogen were estimated to have differed by 20-25 kg/ha.

The comparisons gave little promise that the size of the nitrogen residue left by a legume could be estimated from its yield, or using other records that could easily be taken on farms.

INTRODUCTION

Break crops give rise to the largest adjustments in amounts of fertiliser nitrogen advised for winter cereals in the UK. Allowances for the nitrogen residues from oilseed rape, beans, peas or potatoes are considered similar (MAFF, 1988). However, they range from 25 to 100 kg/ha N depending on the soil texture (and thus the retention of the residue over winter).

Experiments to support these adjustments have not been well summarised and can be subject to a number of different interpretations. For example, De *et al.* (1983) found that tropical legumes increased yield of the following rice crop at all levels of fertiliser nitrogen but nevertheless expressed residual effects just in terms of fertiliser amounts (36-67 kg/ha N), ignoring the non-nitrogenous effects of the legumes.

There is evidence in the literature that field beans (*Vicia faba* L.) have a residual effect through a nitrogen residue. Widdowson *et al.* (1987) found a mean difference between wheat and field beans (*Vicia faba*) of 39 kg/ha N in nitrate nitrogen to 90 cm depth in November, Dyke & Slope (1978) found the residual effect of spring beans to be equivalent to 44 kg/ha fertiliser nitrogen applied to the next spring barley crop grown at Rothamsted, and Prew & Dyke (1979) found that spring beans caused a residual effect on winter wheat equivalent to 50 kg/ha N from fertiliser.

Tas (1983) working at ADAS Drayton reported residual effects of beans of about 50 kg/ha N and Bowerman & Clare (1976) working at ADAS Boxworth found that, over three seasons, beans left a residue equivalent to about 75 kg/ha N applied in the autumn or, assuming response relationships (as shown in Figure 2 below), a response similar to 63 kg/ha N applied in spring.

Although the area of peas (*Pisum sativum* L.) grown in the UK is more extensive than that of beans, especially in the eastern counties, less is known of their residual effects. Work at ADAS Cambridge (Bloom, 1986) has shown their effect to be similar and more consistent than that of oilseed rape (*Brassica napus* L.), although these comparisons were confounded with a small soil type difference. Observations in one further season indicated an effect of peas greater than that of field beans (Vaidyanathan, 1984). Studies in Finland have also shown beans to have less of an effect than peas (Varis, 1983).

Senaratne & Hardarson (1988) found in Austria, using a small fertiliser supplement of 20 kg/ha N, that beans left slightly more nitrogen than peas and peas more than barley, (both caused a net depletion of soil nitrogen compared to bare fallow), but response of the following sorghum was very similar after both legumes. In discussion they state that residues from legumes with high harvest indices cannot be large; root and nodule residues have seldom been estimated at more than 10% of the total nitrogen in the legume crop.

Jensen & Haahr (1990) recently reported pea residues to be equivalent to 20-30 kg/ha fertiliser N, whereas oilseed rape residues were equivalent to 30-60 kg/ha N.

Source of the nitrogen residue

The residual effects reported in agronomic experiments are relatively small compared to the amounts of nitrogen that are estimated to be fixed by temperate legume crops. Roughley *et al.* (1983) found reports of fixed nitrogen from *Vicia faba* to vary between 45 and 552 kg/ha N and Sprent & Bradford (1977) concluded that, depending on growing conditions, *Vicia faba* could fix more than 600 kg/ha N.

In Australian conditions, Herridge (1982a & 1982b) reports that, although large (and rather variable) amounts of nitrogen are fixed by legumes, only small amounts appear to be available to the following crop; they attribute the difference to losses through leaching and denitrification, and soil dryness restricting availability of the residues.

Jensen (1989) found that most of the nitrogen obtained by fixation in peas was removed in the pea grain; only 25% was left in the form of crop residues. So there was no net improvement in the nitrogen status of the soil, and residual effects were similar to those after oats. He found that immobilisation of soil nitrogen can occur if the pea residues have a small nitrogen concentration, but removal of pea straw had little effect on the residual effects of peas. Haystead (1983) reports that residue decomposition is relatively slow, most is retained in the soil organic matter, but there also appear to be large losses; suggested causes are volatilization, and wind removal of material, as well as leaching.

Fox *et al.* (1990) found that legumes with less than 20 g/kg N immobilised nitrogen for the first six weeks after incorporation. The rates of mineralisation, although uncertain in their absolute estimation, could be predicted on a relative scale from the (lignin + polyphenol):nitrogen ratio of the leguminous residue.

On the other hand, Dyke & Prew (1983) assume that the root system is the main source of residual nitrogen left by field beans, because most of the nitrogen in haulm and pods is either burned, blown or carted off the field.

Given the considerable variability in yield and nitrogen partitioning of legume crops, differences in residual effects may be explained by first observing size and productivity of the legume crop (Haystead, 1983). However, it is still not clear from the literature whether large legume crops leave large residues because their root nodules have a large source of energy to drive the fixation of N, or whether they leave small residues because the crop has a large demand for the N fixed.

Other features of the legume effect

It is also a point of confusion in the industry that wheat yields tend to be larger after break crops than after cereals and thus there appears to be justification for extra N to feed the greater yield, so negating any allowance for the N residue from the break. This inference was not supported in previous work at ADAS Cambridge (Vaidyanathan *et al.*, 1987); it was shown that cereals tended to make better use of the N they take up after break crops than where they follow a cereal. It has been suggested not only that cereals after break crops are subject to less infection by root diseases, but that soil structure, and thus root exploration, may be improved after a break.

As well as the economic advantages in identifying more precisely the nitrogen requirements after the different break crops, there may also be important implications for the production of adequate grain protein in the breadmaking varieties which are commonly chosen for the first wheat crop after a break crop.

The project reported here was set up to test whether the residual effects of peas and beans can be distinguished and how any distinctions should be interpreted when fertiliser advice is given for a following cereal crop.

METHODOLOGY & DESIGN

In each of the three seasons, 1987-88, 1988-89 and 1989-90, at each of about twelve farms in the eastern & southern counties, three fields of similar soil were selected where winter wheat was to be grown after peas, beans and wheat. Thus comparisons could be made between these previous crops at each site (usually within one farm). The design was such that the comparisons were confounded with field to field differences. Farms had too few fields for replication to be possible within a farm. Thus replication could only be achieved by selecting several farms and accepting some uncertainty in comparisons between previous crops, due to interactions with farm-related factors. It is held that this approach reflects the uncertainty encountered in commercial cereal production, and should allow a better assessment of the importance of any break crop effects than would be provided with the restricted within-field variation which is normally favoured as the background for more conventional crop experimentation.

Soils were all of high clay content (greater than about 20%). Soil series, soil organic matter contents and other site details are shown in Tables 1a-1c. Compared to the soils in fields of peas, there was a tendency for beans to be grown on heavier soils where it was more difficult to achieve a good seedbed. However, there was no statistically significant association between choice of previous crop for a field and the organic matter content of its soil.

For as many of the selected fields as possible estimates of grain yield of the peas, the beans and the cereal and their grain nitrogen concentrations were obtained from the farmer. Also, at a point of relatively uniform soil in each field the total crop dry weight and grain weight were determined at or shortly before harvest of the peas, beans and cereal, by cutting, threshing and analysing (using Kjeldahl's method) all crop material from 6 quadrats, each of one square metre.

Winter wheat was then drilled on all fields and was husbanded according to the commercial practice of the farmer, except that the only nitrogen dressing was that applied to individual plots of at least 70 m^2. Nil and 240 kg/ha N were tested in all seasons; other amounts were also tested in some seasons: 180 kg/ha N in 1989, 120 kg/ha N in 1990, and in 1990 following wheat 360 kg/ha N. Treatments were randomly arranged within each of three replicate blocks.

Nitrate nitrogen and ammonium nitrogen in the soil to a depth of 90 cm were determined in autumn and early spring, crop nitrogen was determined in early spring, and grain yields, grain moisture and grain nitrogen concentrations were determined for all plots at harvest.

After inspecting differences between replicates for any undue within-field variation, mean values of the measurements were calculated for each field and all data were then analysed for variation due to seasons, previous cropping and any interaction between them; variation due to seasons was extracted from the site(farm)-season stratum and variation due to previous cropping was extracted from the site-season-field stratum.

Many sources of uncontrolled field to field and crop to crop variation occurred. These included :

- variation in soil texture, P, K, and Mg status,
- differences in soil stone content,
- differences in soil depth above chalk,
- inclusion of oats as a previous crop instead of wheat,
- differences in lodging of previous crops,
- differences in disposal of previous crop residues,
- different varieties of previous crops, and wheat crops,
- inclusion of vining peas instead of dried peas,
- sowing dates ranging from September to December,
- variable competition from blackgrass,
- uncertain records of nitrogen applications to previous cereals,
- variable establishment of wheat plants,
- inclusion of a wheat crop with 15% of barley volunteers,
- differences in take all infection of wheat crops,
- differences in virus infection of the wheat crops,
- differences in pesticide applications,
- differences in drought effects on the wheat crops,
- differences in lodging of the wheat crops, and
- vandalism to a ripe wheat crop.

The main differences between fields are shown in Tables 1a-1c. Where circumstances were judged to compromise the comparisons, the trial on that field was aborted. A criterion was adopted by which fields were included in the final set of data used to compare previous crop effects only if the characteristics of the three fields at a site, their previous crops and their test crops of winter wheat were such that the advice given for the wheat crops at the time of nitrogen application (as currently recommended; MAFF, 1988) would not have been adjusted on account of factors other than previous crops described as 'a cereal' or, 'peas or beans'.

Interpretation of nitrogen responses

Soil supply of nitrogen to the crop was compared through direct measures of soil mineral nitrogen to 90cm, the crop uptake in spring where no fertiliser nitrogen was applied, and grain nitrogen uptake at harvest where nil nitrogen was applied.

From the relationship shown in Figure 1, between grain yield with 240 kg/ha N and maximum grain yield where this was achieved with amounts other than 240 kg/ha N, it has been taken that effects on yield potential (yield unrestricted by nitrogen supply) of these winter wheat crops are indicated with adequate accuracy by the yield achieved at 240 kg/ha N.

Further, it was taken that effects of previous cropping on optimum nitrogen amounts could be inferred without resort to multi-level nitrogen experiments. Previous analysis of multi-level response experiments has shown that 83% of the variation in optimum nitrogen can be accounted for simply by the yield response due to the application of 240 kg/ha N (Figure 2).

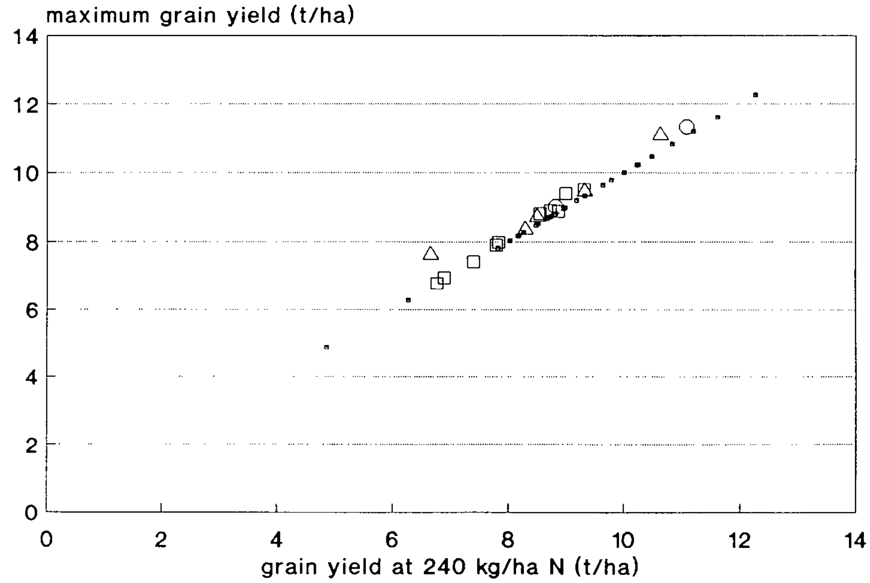

Figure 1. *For experiments with more than one level of applied N the relationship between the maximum grain yield (triangles 120 kg/ha, circles 240 kg/ha, squares 360 kg/ha) and the grain yield achieved with 240 kg/ha N.*

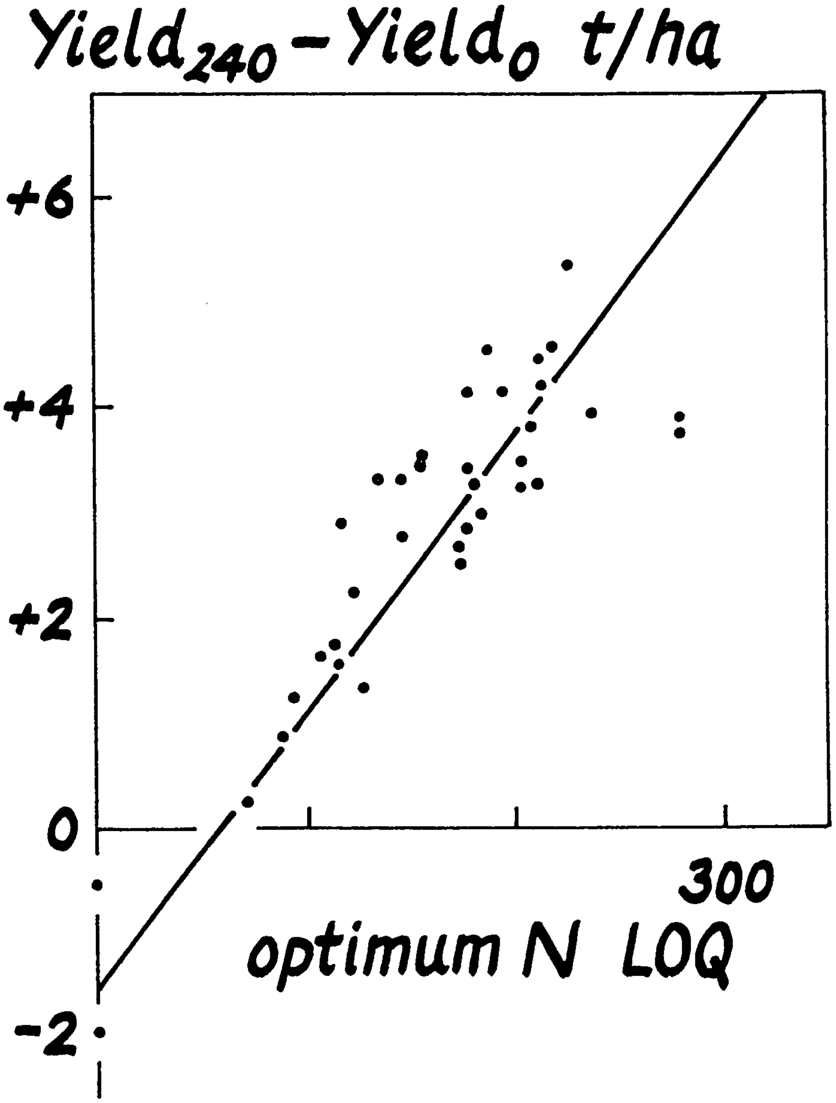

Figure 2. *Relationship between the optimum amounts of applied N (determined by differentiating an exponential function with a linear term fitted to the grain yields achieved with 0, 80, 120, 160, 200, 240 and 280 kg/ha N) and the response in grain yield from nil to 240 kg/ha N applied. Data from Bloom (1987).*

Table 1a. *Characteristics of fields and crops at the ten sites in eastern & southern England where wheat (W), combined peas (P; vined peas, P) and winter field beans (B; spring beans, B) had been grown in 1987.*

Site	Prev crop	Soil series	Soil OM %	Crop res. disposal	Variety	Sow date	Harv date
Balsham,	W	Hanslope	2.1	Bale	Galahad	7.10	13.9
Cambs.	P	Hanslope	2.6	Chop	Mercia	.9	13.9
	B	Hanslope	2.4	Chop	Mercia	.10	13.9
Barkway,	oats	Swaffham Prior	2.8	NA	NA	NA	11.9
Herts.	P	Upton 1	2.6	NA	NA	NA	11.9
	B	Upton 1	2.9	NA	NA	NA	11.9
Colesdon,	W	Hanslope	NA	Burn	Slepjner	19.10	26.8
Beds.	P	Hanslope	2.6	Burn	Slepjner	24.10	26.8
	B	Hanslope	2.8	Burn	Slepjner	26.10	26.8
Combs,	W	Beccles 3	2.5	Chop	Slepjner	27.9	18.8
Suffolk	P	Beccles 3	2.4	Bale	Avalon	31.10	30.8
	B	Beccles 3	2.3	Chop	Rendzvs	23.10	30.8
Rettendon,	W	(no site)					
Essex	*P*	Winsor	2.1	Burn	Mercia	4.10	23.8
	B	Winsor	2.3	Burn	Mercia	4.10	23.8
Snettisham,	W	(no site)					
Norfolk	P	Wallasea	1.8	Chop	Hornet	19.10	30.8
	B	Wallasea	1.2	Chop	Hornet	19.10	30.8
Thaxted,	W	Hanslope	2.6	Burn	Galahad	30.10	27.8
Essex	P	Hanslope	2.4	Chop	Avalon	7.12	5.9
	B	Hanslope	3.6	Chop	Mercia	7.12	5.9
Wereham,	W	Beccles 1	2.9	Burn	Slepjner	26.9	22.8
Norfolk	P	Beccles 1	2.7	Bale	Galahad	30.9	22.8
	B	Beccles 1	2.7	Burn	Apollo	24.9	22.8
Adisham,	W	Coombe	2.6	Chop	Slepjner	1.10	23.8
Kent	*P*	Coombe	2.9	Chop	Avalon	3.10	13.8
	B	Coombe	NA	Chop	Avalon	3.10	13.8
Durston,	W	Whimple	1.1	Bale	Mercia	28.9	11.8
Devon.	P	Whimple	2.2	NA	Avalon	27.9	5.9
	B	Whimple	1.8	NA	Mercia	7.10	11.8
Sites aborted or providing only partial data :							
Braintree,	W	(no site)					
Essex	P	Hanlsope	NA	NA	Brock	NA	3.9
	B	Hanslope	NA	NA	Avalon	NA	26.8
Burton	W	NA	NA	NA	NA	NA	NA
Pedwardine,	P	NA	NA	NA	NA	NA	NA
Lincs.	B	NA	NA	NA	NA	NA	NA
Grainsby,	W	NA	NA	Burn	NA	NA	NA
Lincs.	P	NA	NA	Burn	NA	NA	NA
	B	NA	NA	Burn	NA	NA	NA
Keysoe,	W	Hanslope	NA	Burn	NA	NA	NA
Beds.	P	Hanslope	NA	Chop	NA	NA	NA
	B	Hanslope	NA	Chop	NA	NA	NA

Table 1b. *Characteristics of fields and crops at the eleven sites in eastern England where wheat (W), peas (P) and beans (B) had been grown in 1988.*

Site	Prev crop	Soil series	Soil OM %	Crop res. disposal	Variety	Sow date	Harv date
Balsham,	W	Hanslope	2.1	Bale	NA	NA	21.8
Cambs.	P	Swffhm Prior	2.4	Chop	Mercia	30.9	16.8
	B	Hanslope	2.6	Chop	NA	NA	21.8
Combs,	W	Hanslope	2.5	Chop	Hornet	.11	2.8
Suffolk	P	Hanslope	2.4	Bale	Brock	.10	16.8
	B	Hanslope	2.3	Chop	Apollo	.11	20.8
Cornish Hall	W	Hanslope	3.0	Burn	Galahad	6.10	13.8
End, Essex	P	Hanslope	3.0	Chop	Hornet	1.10	13.8
	B	Hanslope	2.4	Chop	Hornet	21.9	13.8
Fincham,	W	Newmarket-1	2.2	Chop	Rendzv's	28.9	19.8
Norfolk	P	Newmarket-1	2.0	Chop	Slepjner	22.9	19.8
	B	Newmarket-1	2.2	Chop	Slepjner	4.10	19.8
Keysoe,	W	Hanslope	3.2	Burn	Riband	1.10	18.8
Beds.	P	Hanslope	2.8	Chop	Riband	29.9	18.8
	B	Hanslope	2.9	Chop	Hornet	2.10	18.8
Rettendon,	W	Winsor	3.0	Burn	Gallahad	13.10	31.7
Essex	P	Winsor	2.4	Chop	Avalon	2.10	31.7
	B	Winsor	2.7	Chop	Avalon	2.10	31.7
Thaxted,	W	Hanslope	2.9	Chop	Mercia	5.10	14.8
Essex	P	Hanslope	2.9	Chop	Avalon	30.9	27.8
	B	Hanslope	3.0	Chop	Avalon	4.10	29.8
Wereham,	W	Wickham-2	3.0	Bale	Apollo	21.9	28.7
Norfolk	P	Wickham-2	5.0	Chop	Apollo	22.9	28.7
	B	Wickham-2	3.2	Chop	Apollo	21.9	28.7
Grainsby,	W	Holderness	1.5	Burn	Mercia	6.10	25.8
Lincs.	P	Holderness	1.8	Burn	Mercia	15.10	25.8
	B	Holderness	2.2	Burn	Mercia	15.10	25.8
Sutton	W	Agney	4.8	Burn	Hornet	26.9	13.8
Bridge,	P	Agney	5.0	Burn	Slepjner	3.10	13.8
Lincs.	B	Agney	3.1	Burn	Brigand	15.10	13.8
Adisham,	W	Coombe	3.0	NA	Mercia	NA	8.8
Kent	P	Coombe	3.6	NA	Slepjner	NA	8.8
	B	Coombe	2.8	NA	Hornet	NA	15.8

Table 1c. *Characteristics of fields and crops at the nine sites in eastern England where wheat (W), peas (P) and beans (B) had been grown in 1989.*

Site	Prev crop	Soil series	Soil OM %	Crop res. disposal	Variety	Sow date	Harv date
Cardington, Beds.	W	Evesham	3.4	Burn	Mercia	11.10	8.8
	P	Hanslope	2.9	Chop	Riband	7.10	7.8
	B	Hanslope	3.0	Chop	Apollo	20.9	7.8
Combs, Suffolk	W	Hanslope	2.9	Burn	Hornet	15.11	14.8
	P	Hanlsope	3.4	Chop	Norman	15.10	14.8
	B	Hanslope	3.1	Chop	Slepjner	23.10	14.8
Cornish Hall End, Essex	W	Hanslope	3.4	Burn	Hornet	7.10	8.8
	P	Hanslope	2.9	Chop	Pastiche	19.9	8.8
	B	Hanslope	2.4	Chop	Hornet	26.9	15.8
Cranfield, Beds.	W	Evesham	3.8	Chop	blend	24.10	17.8
	P	Evesham	2.7	Chop	Riband	30.10	17.8
	B	Hanslope	3.5	Chop	Fortress	16.10	17.8
Hinxworth, Herts.	W	Milton	2.8	Burn	Hornet	4.10	4.8
	P	Milton	2.8	Chop	blend	13.10	4.8
	B	Milton	2.4	Chop	Apollo	7.10	4.8
Thaxted, Essex	W	Hanslope	2.3	Burn	Apollo	28.9	NA
	P	Hanslope	2.2	Chop	Slepjner	10.10	4.8
	B	Hanslope	2.7	Chop	Avalon	18.10	10.8
Minningsby, Lincs.	W	Cannamore	3.4	Bale	Hornet	23.10	28.8
	P	Cannamore	3.3	Bale	Hornet	23.10	28.8
	B	Cannamore	3.4	Chop	Hornet	30.10	28.8
Sutton Bridge, Lincs.	W	Agney	4.3	Burn	Apollo	26.10	13.8
	P	Agney	4.4	Burn	Haven	15.10	13.8
	B	Agney	4.0	Burn	Hornet	23.10	13.8
Thornhaugh, Cambs.	W	Elmton 1	2.4	Burn	Slepjner	21.10	9.8
	P	Elmton 1	2.4	Chop	Slepjner	21.10	9.8
	B	Elmton 1	2.4	Chop	Slepjner	21.10	9.8

RESULTS

Performance of 'previous' crops

For crops preceding the wheat tested in this experiment, the yields reported by farmers (Table 2) did not relate well to yields measured from hand-taken samples (Table 3). The farmer was assessing the whole field, whereas hand sampling was from an area especially selected for uniformity and therefore avoiding unproductive patches. The difficulties of avoiding bias when making measurements of yield by hand have been discussed elsewhere (Bloom, 1985). However, as well as bias in the measurements, it is likely that the discrepancies reflect the significant within-field variation that is particularly common with field legumes (Gates *et al.*, 1983). The hand measured yields have been taken as more appropriate for interpreting residual effects of the crops in this study.

The tables in this Section show attributes averaged for cereal, pea and bean crops and for each of the three seasons, 1987-9. Figures in the body of each table are means of about ten sites.

Table 2. *Previous crop yield - determined on the farm (t/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*#	7.27	2.70	2.43	4.13	
	1988-89	7.32	4.33	4.89	5.51	0.45 **
	1989-90	8.50	4.10	4.16	5.59	
	Mean	7.73	3.79	3.94		
	SED		0.31 ***			0.67 *

\# In all tables, the first year given for a *Season* is that when the 'previous' crops were harvested and the second year indicates when the test crops of winter wheat were harvested.

* asterisks indicate the level of statistical significance (~ $P<0.10$; * $P<0.05$; ** $P<0.01$; *** $P<0.001$) of the variance ratio relating to each SED. The SED for interactions between *Previous crop* and *Season* are only given where these were statistically significant.

Table 3. *Previous crop yield - determined by hand (t/ha)*

		Previous crop :				
		CEREAL	PEAS	BEANS	Mean	SED
Season :	1987-88	7.78	4.36	4.05	5.40	
	1988-89	9.26	4.36	6.11	6.58	0.53 *
	1989-90	9.05	4.92	4.31	6.09	
	Mean	8.55	4.45	4.87		
	SED		0.37 ***			

In 1987 legume crops, particularly peas, were less successful than normal, probably because of the wet and dull conditions during seed formation. Legumes in 1988 and 1989 performed satisfactorily, and beans appeared to out-yield peas; this is more evident from the hand-harvested samples than from the results reported by the farmers. Bean and pea yields did not differ significantly but, as expected, cereal yields were always greater than legume yields.

Grain yield, expressed as a proportion of final crop dry matter (DM harvest index, Table 4), appeared to be relatively stable, irrespective of crop or season; there were no significant differences between crops.

Table 4. *Previous crop's harvest index (DM)*

		Previous crop :				
		CEREAL	PEAS	BEANS	Mean	SED
Season :	1987-88	0.44	0.50	0.43	0.46	
	1988-89	0.49	0.45	0.47	0.47	0.040
	1989-90	0.46	0.48	0.41	0.45	
	Mean	0.46	0.48	0.44		
	SED		0.021			

Table 5. *Previous crop's total dry matter (t/ha)*

		Previous crop :				
		CEREAL	PEAS	BEANS	Mean	SED
Season :	1987-88	14.9	7.2	8.0	10.1	
	1988-89	16.2	8.0	11.0	11.7	1.03
	1989-90	16.9	9.4	9.6	12.0	
	Mean	15.7	7.9	9.4		
	SED		0.48 ***			

Thus the differences in grain yield were largely reflected in differences in total crop dry matter (Table 5). However, there was some tendency for the harvest index of beans to be small, so beans produced more DM than peas, especially in 1988.

The quantity of nitrogen taken off in the grain of the previous crops proved to be very much affected by season (Table 6). However, seasonal effects differed markedly for each crop. Average offtake in peas never exceeded both beans and cereals. As can be seen later for the test crops (Table 17), wheat yielded well in 1989, and showed a proportionately large nitrogen offtake. Beans were most variable, as is commonly found (Gates *et al.*, 1983). They showed a 2-fold difference between seasons, and gave both the largest (in 1988) and the smallest (in 1989) average nitrogen offtakes.

Table 6. *Previous crop's grain nitrogen - determined by hand (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	140	131	134	135	
	1988-89	140	135	220	165	16.3
	1989-90	174	148	115	146	
	Mean	146	136	163		
	SED		10.0 *			28.0 ***

Table 7. *Previous crop's straw & chaff nitrogen (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	60	51	46	52	
	1988-89	56	58	47	54	10.9
	1989-90	63	36	51	50	
	Mean	59	51	47		
	SED		5.1			

There were no significant differences in amounts of nitrogen taken up in the haulm or straw of previous crops. However, the amounts returned to the next crop did vary because of differences in the way the farm disposed of the residues (see Tables 1a-1c). Some estimates of these amounts were examined in relation to residues measured later, assuming that burning disposed of all and baling disposes of half the nitrogen in chaff and straw or haulm.

Table 8. *Previous crop's straw & chaff C:N ratio*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	67	31	42	47	
	1988-89	66	33	50	50	3.23
	1989-90	61	57	42	53	
	Mean	65	39	45		
	SED		2.67 ***			5.53 ***

Where residues were incorporated in the soil before establishment of the wheat, the potential for mineralisation of their nitrogen (or conversely immobilisation of inorganic soil N) is indicated by the nitrogen concentration of the material, expressed here (Table 8) as the C:N ratio. The significantly larger C:N ratio for beans than for peas may indicate that residual nitrogen from beans would be slower to mineralise than from peas. However, there were also large differences due to season, perhaps indicating scope to assess crops on an individual basis.

Table 9. *Previous crop's nitrogen harvest index*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	0.71	0.72	0.75	0.73	
	1988-89	0.76	0.68	0.82	0.76	0.047
	1989-90	0.74	0.82	0.67	0.74	
	Mean	0.73	0.72	0.76		
	SED		0.027			0.079 *

Of the total nitrogen taken up by the crops, the proportion that was harvested in grain (nitrogen harvest index, Table 9) was fairly consistent across the three seasons for cereals but was quite variable for the legumes. The values for wheat are smaller than was recorded in other experiments by this Department

(Vaidyanathan & Rochford, personal communication) and, given that large nitrogen applications tend to depress nitrogen harvest index, this may indicate that nitrogen usage on these wheat crops was super-optimal. The mean amount used was 200 kg/ha N (standard deviation, 38 kg/ha N), producing a mean grain yield of 7.7 t/ha.

It can be supposed that nitrogen is partitioned between grain and straw on the basis of the relative concentrations of nitrogen in the two tissues. Given this, it appears (data not shown) that beans were more successful in depleting their haulm of nitrogen than peas or cereals; nitrogen concentration in bean haulm was about a quarter of that in the grain itself whereas nitrogen concentrations in cereal straw and pea haulm were only about a third of the nitrogen concentrations in their grain.

Perhaps because of the contrast in nitrogen concentration between grain and straw, the differences between crops in nitrogen harvest index were more consistent than for DM harvest index. Nitrogen harvest index for beans was greatest in 1988 and least in 1989; the converse was true for peas. Large nitrogen harvest indices thus coincided with the more successful seasons for grain production.

There was considerably more nitrogen taken up by the bean crop in 1988 (average 281 kg/ha) than in other seasons or by other crops (Table 10) because grain nitrogen was the dominant component of nitrogen uptake at harvest.

Table 10. *Previous crop's total crop nitrogen (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	198	182	181	187	
	1988-89	224	193	271	229	17.3 *
	1989-90	237	184	167	196	
	Mean	217	186	207		
	SED		8.1 **			23.0 ***

Effects of 'previous' crops over winter

The data (above) on performance of the different 'previous' crops was collected in order to interpret differences in the nitrogen residues they left. The residues have been measured in a number of different ways, both directly on the soil and indirectly by performance of the wheat crop.

The tables in this Section show attributes averaged for the soils (or the winter wheat crops grown) after the cereal, pea and bean crops above. Figures in the body of each table are again means of about ten sites.

Table 11. *Soil mineral nitrogen in autumn 0-90cm (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	42	59	55	52	
	1988-89	56	96	65	73	12.0 **
	1989-90	86	100	88	91	
	Mean	58	82	67		
	SED		5.5 ***			

Table 11 shows that on average residues measured in the autumn as nitrate and ammonium nitrogen to 90 cm depth were, as suspected, significantly greater after peas than after beans, and also significantly greater after beans than after cereals. However, there was considerable seasonal variation. Residues in 1987 were generally small and legume residues were not apparently very much greater than from cereals. Denitrification (and perhaps, on the lighter or better structured soils, some leaching) in the wet autumn of 1987 is the most likely explanation.

Cereal nitrogen residues were also small in the autumn of 1988 compared to measurements made by this Department over six previous seasons, and the residues due to different previous legume crops, although significantly larger for peas in a statistical sense, were not so pronounced. The autumn of 1988 was warm and relatively dry so that conditions were not conducive to losses of soil nitrogen through leaching or denitrification. Microbial immobilisation of the soluble N, although not normally expected in these autumn conditions, would seem to be the most probable cause of the low levels of available nitrogen.

In general, over all seasons, the difference between cereals and legume residues, although statistically significant, appeared surprisingly small compared to previous experience.

When the residues were again measured in spring (Table 12) they were smaller, due to crop uptake, denitrification, and probably some leaching, and the differences between previous crops and seasons, although similar to those in autumn, were less consistent and were not statistically significant.

Table 12. *Soil mineral nitrogen in spring 0-90cm (kg/ha)*

		Previous crop : *CEREAL*	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	43	40	40	41	
	1988-89	47	66	50	54	12.7
	1989-90	65	69	61	65	
	Mean	50	56	49		
	SED		6.7			

Crop uptake by wheat over-winter usually depends strongly on when the wheat was sown. Sowings were generally made earlier in 1988 than in 1987 or 1989 and crop uptakes were greatest in that season. Although previous cropping had some influence on sowing dates, (sowings after cereals were about 7-10 days earlier than after legumes in 1987 but 4 days later than after legumes in 1989), the measurements of crop uptake (Table 13) showed, in each season, largest uptake after peas and smallest uptake after cereals.

Table 13. *Total crop nitrogen in spring (kg/ha)*

		Previous crop : *CEREAL*	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	15	21	17	18	
	1988-89	25	34	32	30	3.5 **
	1989-90	23	26	27	25	
	Mean	20	27	25		
	SED		2.7			

Crops which exhibit low nitrogen concentrations may have had some restriction in growth due to insufficient nitrogen being available for uptake, whereas those with a large nitrogen concentration are likely to have been restricted by factors other than nitrogen availability. Thus to an extent, factors affecting over-winter growth can be inferred from the nitrogen concentration of the crops in spring (Table 14).

Crop nitrogen concentrations were small after the autumn of 1987, when soil nitrogen residues were also found to be small. Although no wheat crop showed levels which would have been associated with deficiency, crop uptakes of nitrogen in spring were lowest in this season. Mean concentrations were always smaller after cereals than after the legumes. It is likely that growth was restricted by small soil nitrogen supplies in these instances.

Table 14. *Crop nitrogen in spring (%)*

		Previous crop : *CEREAL*	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	3.0	3.1	3.2	3.1	
	1988-89	3.9	4.3	4.2	4.1	0.206 ***
	1989-90	3.5	4.1	4.0	3.9	
	Mean	3.4	3.8	3.8		
	SED		0.131 *			

The differences due to previous crops that were shown by analysis of soil mineral nitrogen in autumn were less consistent when soil plus crop nitrogen was assessed in spring (Table 15), although the season 1987-88 still showed small residues. This was because, in contrast to previous seasons in the 1980s, there appeared to be some net mineralisation of nitrogen over-winter (Table 16). Wheat uptake overwinter tended to be slightly larger after the break crops than after cereals but, with other processes giving variable changes at the same time, the levels of soil plus crop nitrogen had not decreased by the spring as they usually do, and they did not significantly differ according to previous crop.

Table 15. *Soil plus crop nitrogen in spring (kg/ha)*

		Previous crop : *CEREAL*	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	53	58	53	55	
	1988-89	66	90	79	78	12.7 *
	1989-90	88	94	88	90	
	Mean	67	78	71		
	SED		6.5			

Differences between two measurements, as in Table 16, tend to show amplified variability. Thus it is not surprising that comparisons between previous crops or seasons did not prove to be statistically significant. However, it is worth noting that there appeared to be less net mineralisation after peas than after cereals or beans; it was the peas' haulm which showed the smallest C:N ratio (Table 8) and therefore perhaps would be expected to have completed its decomposition in autumn.

Table 16. *Autumn to spring change in soil plus crop nitrogen (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	+12	+6	+3	+7	
	1988-89	+14	+1	+18	+11	12.0
	1989-90	+6	-2	+10	+4	
	Mean	+11	+2	+10		
	SED		5.9			

Effects of 'previous' crops at harvest

At each site, the maximum grain yield was normally achieved with 240 kg/ha N; where maxima were achieved with other nitrogen amounts they were only markedly different (about 1 t/ha) than at 240 kg/ha at one site (Rettendon after peas) where there was lodging. It was thus concluded that yield at 240 kg/ha N provided an adequate estimate of yield, unrestricted by nitrogen (Figure 1).

Maximum yields across sites and seasons ranged from 7 to more than 12 t/ha. Yields in 1989 were generally larger than in 1988 or 1990 (Table 17). In brief, seasonal effects appeared to be related to poor establishment in 1987-88, warm and sunny conditions in 1989, and sunny but unusually warm and dry conditions in 1990.

With 240 kg/ha N, yields after peas and beans were not statistically distinguishable but were respectively 1.26 and 1.0 t/ha better than after cereals. This 'break effect' was similar in each of the three seasons studied and was much as was expected from the many similar comparisons made in other work (e.g. Vaidyanathan *et al.*, 1987).

Table 17. *Grain yield with 240 nitrogen (t/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	7.21	8.17	8.02	7.80	
	1988-89	8.36	9.79	9.18	9.11	0.491 *
	1989-90	7.48	8.90	8.94	8.44	
	Mean	7.70	8.96	8.70		
	SED	0.244 ***				

Grain yields without applied nitrogen ranged from 3 to 9 t/ha but fertiliser nitrogen increased yields further on all but two fields (Wereham and Rettendon after peas in 1988-89). Grain yields without addition of fertiliser nitrogen were expected to be strongly influenced by the nitrogen available from the soil. However, the seasonal averages of nil-N yields were large in 1989 and small in 1988, reflecting the pattern of fertilised yields, rather than the seasonal pattern of measured residues (e.g. Table 11).

There was no statistically significant distinction between nil-N yields after peas and after beans, but both were significantly larger than after cereals. This difference is likely to have been influenced not only by the greater nitrogen residues left by the legumes but also by the greater yield potential resulting from reduced levels of disease.

The nil-N yields after cereals in 1990 were larger than in the 2 previous years. A contributory factor may have been that straw was incorporated at only 1 site of the 1990 test crops compared to 2 or 3 sites in earlier years (Table 1).

Table 18. *Grain yield with nil nitrogen (t/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	3.34	5.09	5.21	4.55	
	1988-89	4.34	6.72	5.79	5.62	0.560
	1989-90	4.70	5.82	5.98	5.50	
	Mean	4.09	5.88	5.64		
	SED	0.271 ***				

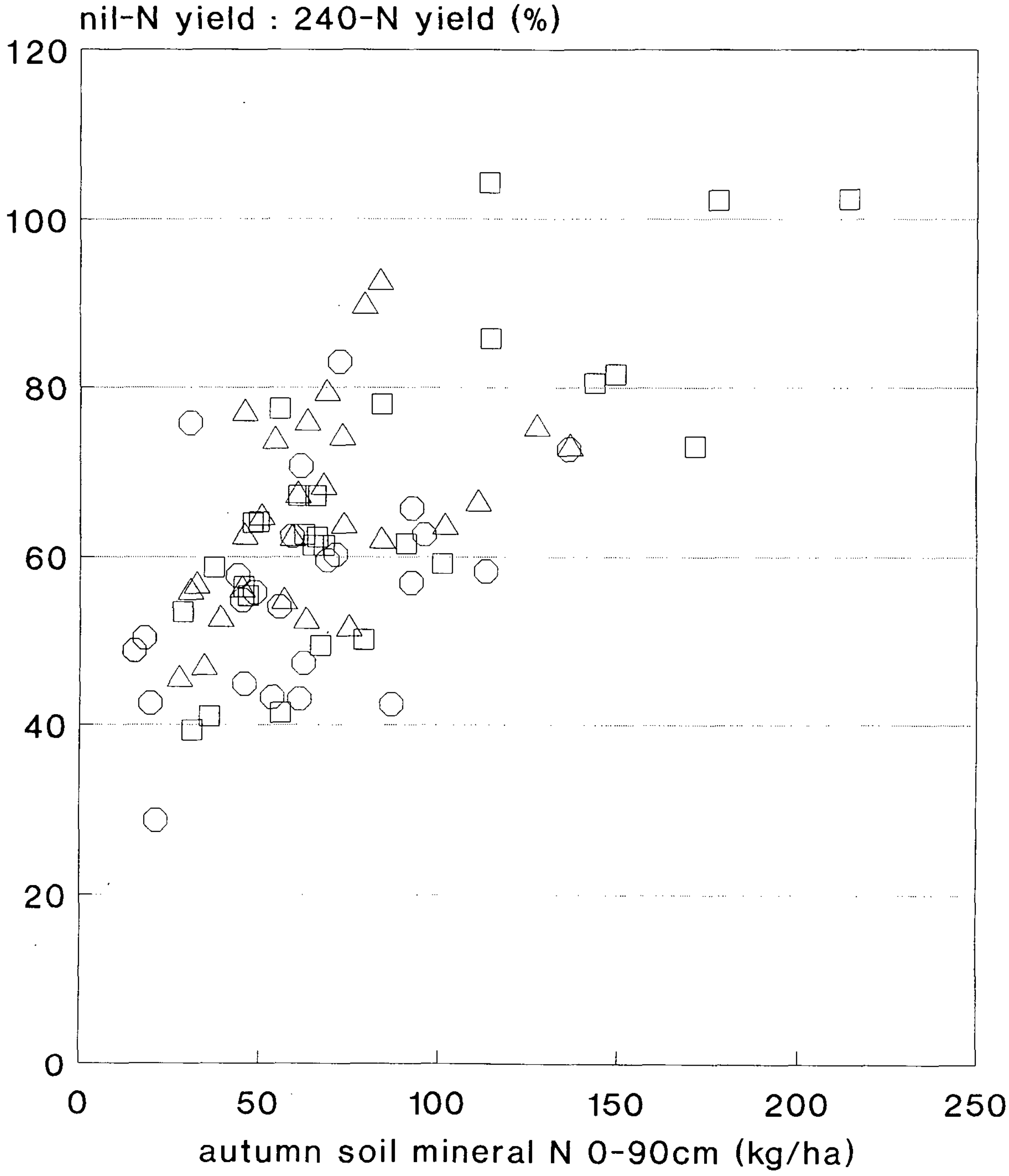

Figure 3. *The relationship between soil mineral nitrogen (kg/ha) measured in autumn and grain yield of winter wheat with no applied N as a proportion of the yield with 240 kg/ha N applied. The wheat was grown after a cereal (circles), peas (squares) or beans (triangles).*

Because the grain yield with 240 kg/ha N is a good measure of yield unrestricted by nitrogen (Fig. 1), the difference between the grain yield with 240 kg/ha N and with no nitrogen must be as good a measure of the yield response achievable through use of N. It has been found in previous work by this Department (Fig. 2) that this relates well to the amount of nitrogen needed to achieve the economic optimum yield; a response of 1 t/ha grain has been shown to relate to a need for 40-50 kg/ha fertiliser N. Table 19 thus provides for the most direct economic inferences of all the data presented in this paper.

There were no statistically significant differences between the three seasons in yield response to applied N; seasonal effects on both the fertilised (Table 17) and unfertilised yields (Table 18) were similar and were not reflected in their differences. Responses after cereals were variable and appeared to reflect the measured soil nitrogen residues; in 1989-90, when cereal residues were largest, responses were no greater than after legumes. Soil mineral nitrogen measured in autumn accounted for 41% of the variation in yield with no N, expressed as a proportion of yield with 240 kg/ha N (Fig. 3).

Yield responses after peas were on average very consistent over the three seasons. Responses after beans were more variable but overall were very similar to those after peas.

Table 19. *Response in grain yield to 240 kg/ha nitrogen (t/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	3.87	3.08	2.81	3.25	
	1988-89	4.02	3.07	3.39	3.50	0.512
	1989-90	2.78	3.08	2.96	2.94	
	Mean	3.61	3.08	3.06		
	SED		0.244 *			

The difference between response after cereals and after legumes was little more than 0.5 t/ha. This relates to a difference in fertiliser 'requirement' of only 20-25 kg/ha (Fig. 2), less than the 50-75 kg/ha that would at present be advised in published recommendations for these soils (MAFF, 1988).

On average the proportion of fertilised yield that was produced with no fertiliser nitrogen was a half after cereals and two thirds after a legume (Table 20).

Expressed in this way, the response data show greater consistency than when expressed as absolute responses, probably because any factor which influenced yield but was not related to nitrogen nutrition, such as root diseases and seasonal differences in sunshine and rainfall, exerted a proportionate effect on both fertilised and unfertilised yields.

Table 20. *Proportion of fertilised yield produced without fertiliser nitrogen (%)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	47	62	65	58	
	1988-89	52	70	63	62	5.2
	1989-90	63	65	66	65	
	Mean	53	66	65		
	SED		2.6 ***			6.7 ~

The nitrogen concentrations in grain from unfertilised treatments in experiments in the early 1980's were rarely less than 1.6% (equivalent to 8% protein; Vaidyanathan *et al.*, 1987). The generally small concentrations shown in Table 21 are thus a surprise.

If nitrogen concentration is expressed as its reciprocal (kg DM / kg N), it encourages the thought that these crops without applied nitrogen were using soil nitrogen with improved effectiveness to generate dry matter compared to previously. This 'effectiveness' was particularly pronounced after cereals in 1987-8 at 75 kgDM/kgN, when soil supplies were apparently smallest (Table 11), and was small after beans in 1987-8 (62 kgDM/kgN) and after cereals in 1989-90 (63 kgDM/kgN). Unexpectedly, an effect of previous cropping was only apparent in 1987-8.

Table 21. *Grain nitrogen with nil nitrogen applied (%)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	1.33	1.54	1.62	1.50	
	1988-89	1.42	1.43	1.45	1.44	0.061
	1989-90	1.58	1.40	1.45	1.48	
	Mean	1.43	1.46	1.51		
	SED		0.042			0.090 ***

As is normally the case, grain nitrogen concentrations were considerably increased by the application of 240 kg/ha N (Table 22). In these data, concentrations were small in 1988 compared to later years and were small after cereals compared to after legumes, particularly so in 1988.

It is also normal that grain nitrogen concentrations can be increased with nitrogen amounts somewhat greater than are optimal for grain yield; hence the common use of extra nitrogen to boost protein concentrations of the varieties suitable for breadmaking. Of the crops with varieties suitable for breadmaking in these experiments, only 15 out of 27 would have exceeded 11% protein (2.24 %N) with 240 kg/ha N applied, even though in most cases this level of nitrogen is likely to have been superoptimal in terms of grain yield alone.

Table 22. *Grain nitrogen with 240 kg/ha N applied (%)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	1.71	2.07	2.06	1.95	
	1988-89	2.14	2.18	2.21	2.17	0.0815 *
	1989-90	2.22	2.15	2.14	2.17	
	Mean	2.01	2.13	2.14		
	SED	0.0436 **				0.108 ***

The nitrogen contained in the grain that is harvested, the 'nitrogen offtake', normally represents about 75-80% of the total nitrogen taken into the crop. Thus the nitrogen offtake in treatments with nil applied provides a further measure of the soil supply of N, and thus any residual effects of the previous crops. Table 23 shows there was a significantly larger (20-25 kg/ha) offtake of nitrogen in unfertilised plots after the legumes than after cereals, but there was no statistically significant difference between nitrogen offtakes after peas and beans. Thus in general the nil-N offtakes relate well to the amounts of soil mineral nitrogen measured in autumn (Table 11) and the soil plus crop nitrogen in spring (Table 15).

Assuming that, as is normal (e.g. MacDonald *et al.*, 1989) amounts of soil mineral nitrogen at harvest were very small, the changes in crop plus soil nitrogen between spring and harvest reflect most of any net mineralisation or immobilisation of soil nitrogen that occurred during summer. On average there was net immobilisation after cereals in each season, but after both peas and beans there was little change, with a little net mineralisation in 1987-8 and a little net immobilisation in 1989-90.

Table 23. *Grain nitrogen with nil nitrogen applied (kg/ha)*

		Previous crop : *CEREAL*	 *PEAS*	 *BEANS*	 *Mean*	 *SED*
Season :	*1987-88*	34	66	67	57	
	1988-89	52	86	72	70	8.3
	1989-90	61	69	74	68	
	Mean	49	74	71		
	SED		4.44 ***			

The amount of nitrogen taken off in grain, relative to the amount of applied N, indicates the influence that cropping has on the nitrogen status of the soil. With 240 kg/ha N applied, offtakes were significantly larger after legumes than after cereals, and they were smaller in 1988 than in other seasons. However, the nitrogen offtakes here are generally greater than offtakes that would have occurred with optimum amounts of applied nitrogen and, given the conclusion that optimum amounts would have been 20-25 kg/ha smaller after legumes, 240 kg/ha would have exceeded the optimum after legumes by more than after cereals. Thus, the offtakes after legumes here do not represent those that would have occurred with good fertiliser practice.

The average offtakes in Table 24 differed after the different previous crops mainly because of the differences in yield (Table 17); the average concentrations of nitrogen in the grain (Table 22) were very similar for all previous crops, except in 1988.

Table 24. *Grain nitrogen with 240 kg/ha N applied (kg/ha)*

		Previous crop : *CEREAL*	 *PEAS*	 *BEANS*	 *Mean*	 *SED*
Season :	*1987-88*	105	142	138	128	
	1988-89	151	179	171	167	8.2 ***
	1989-90	139	162	162	154	
	Mean	132	161	157		
	SED		4.1 ***			

The difference between nitrogen offtake with applied nitrogen (Table 24) and nitrogen offtake with nil-N (Table 23) can be expressed as the proportion of the 240 kg/ha N that apparently was recovered in the grain. These results are presented in Table 25, but adjusted to indicate total crop uptake, assuming that grain nitrogen would have constituted 75% of total crop nitrogen (e.g. Table 9). There were statistically significant differences in recovery between seasons but not between previous crops.

It is generally found that uptake of applied nitrogen increases with amounts larger than are optimum for grain yield (Bloom *et al.*, 1988). Thus it is consistent here that an alteration in soil nitrogen status through legume residues did not affect nitrogen recovery, even though 240 kg/ha would have exceeded the optimum by more after legumes than it did after cereals.

Table 25. *Apparent recovery (%) of 240 kg/ha applied N by the crop assuming grain N represented 75% of total crop uptake.*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	38	42	39	40	
	1988-89	55	52	55	54	4.66 *
	1989-90	43	52	49	48	
	Mean	45	48	47		
	SED		6.81			

As nitrogen recovery must be a key determinant of the variability in effectiveness of applied N, it is unfortunate that there has been singularly little success in previous work in accounting for the variation seen between sites and seasons. Recovery of applied nitrogen here, as in previous work, was extremely variable, ranging from 16% to 79%. However, Figure 4 shows that in these data there is a highly significant positive relationship, with grain yield at 240 kg/ha N applied accounting for 35% of the variation in nitrogen recovery.

Inspection of the factors bringing about the variation in yield showed that it was largely the seasonal factors that brought associated changes in recovery, rather than the previous cropping effect. Recovery was also less where soil nitrogen supply was large with the consequence that 42% of the variation in recovery could be accounted for using both the yield with nitrogen applied and the measured soil mineral nitrogen in autumn.

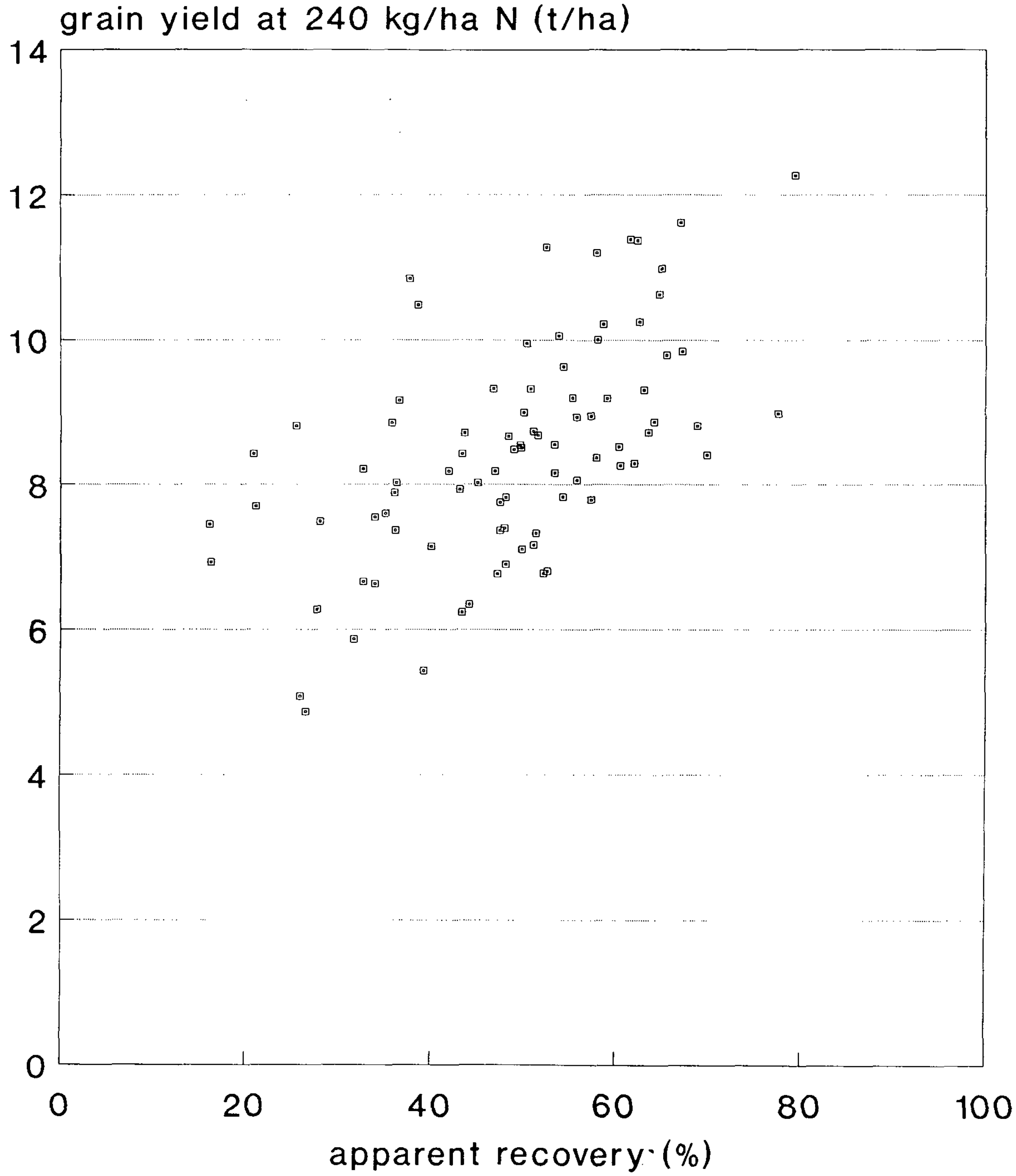

Figure 4. *Relationship between grain yield at 240 kg/ha N and apparent recovery of the applied N calculated as for Table 25.*

DISCUSSION

Comparing separate fields

The design of the experiment described here is unconventional in that the break crop comparisons have been between effects produced in separate fields through normal commercial farming rather than between randomised plots imposed experimentally within one field. Now that the third year of this work is complete it is necessary to assess whether the approach has been productive.

Church & Austin (1983) concluded that site to site variation is generally larger than year to year variation and that the impact of even the most important husbandry decisions is small relative to all variation seen between sites and years. Thus the residual field to field variation could have been so large that the separate field approach could prove counter-productive; interim reports on the first two years of this exercise had few significant differences to report. However, the approach allows considerable savings in the costs of setting up crop comparisons within a field, and it is clearly the case that the residual variation here more exactly represents that level of uncertainty with which cereal growers must contend. By analysing effects over the three seasons, confidence limits in responses to fertiliser nitrogen and their associated determinants have been adequately small, even using the conventional (95%) level of certainty accepted for testing whether differences should be taken as 'real'.

A feature of the work has been the difficulty in obtaining complete and accurate information on the history of fields and the performance of previous crops. There is clearly a need for growers to improve the quality of the records they keep. At first sight it might be concluded that comparisons should be more fully under the experimenter's control. However, it must be noted that, if the factors which are deemed necessary to explain variation in nitrogen response are not normally available to cereal growers, the growers' capacity to apply the more precise advice that may come from this experimentation will necessarily be restricted.

Nitrogen 'allowance' after legumes

The best recent example of a conventional approach to the assessment of break crop effects in conditions relevant to modern cereal growing in the UK is reported by McEwen *et al.* (1989). On the basis of soil mineral nitrogen residues and crop stem counts they adopted a philosophy by which peas were calculated in spring to have reduced the nitrogen requirement of winter wheat by about 40 kg/ha, compared to 30 kg/ha N after spring beans or cultivated fallow. However, using the approach described above (see discussion of Table 19), where requirement is calculated in retrospect from yield responses, the requirements after peas and beans apparently were similar (Table 26).

Table 26. *Responses in grain yield of winter wheat to* about *240 kg/ha N from McEwen et al. (1989). Data are equivalent to those in Table 19. (t/ha)*

		Previous crop : *WHEAT*	*PEAS*	*WBEAN*	*SBEAN*	*OATS*	*FALLOW*
Season :	*1987-88*	4.2	4.5	4.6	3.9	5.9	2.6
	1988-89	6.5	5.4	ND	5.8	6.9	6.1
	1989-90	4.7	2.5	2.8	2.3	5.0	1.6
Mean	*2 years*	4.5	3.5	3.7	3.1	5.5	2.1
	3 years	5.1	4.1	ND	4.0	5.9	3.4

N 'allowances' (@ 50 kg/t) compared to N required after wheat (kg/ha) :

		WHEAT	*PEAS*	*WBEAN*	*SBEAN*	*OATS*	*FALLOW*
Mean	*2 years*		-50	-40	-70	+50	-120
	3 years		-50	ND	-55	+40	-85

The work also showed that cultivated fallow resulted in the largest adjustments in 'requirement', at about 100 kg/ha N. Oats appeared to cause a 40-50 kg/ha larger nitrogen requirement than wheat due mainly to the markedly larger fertilised yield. There was too much variability to distinguish reliably between the effects of oilseed rape, peas and beans; the distinction that might most easily have been argued was a larger allowance after spring beans than after the other break crops. However, it is difficult to generalise with confidence from such comparisons because this experiment was for only one site, because there was considerable seasonal variation, and because of the problems that were encountered in growing break crops in small plots.

The experiment reported here was from the same seasons, but had the advantage of a much more comprehensive coverage of sites. The results corroborate the need to adjust nitrogen applications to wheat after legume crops compared to after cereal crops and support the conclusion that adjustments should be similar after peas and beans, but they indicate that the size of the adjustment should be about 25 kg/ha rather than 40 kg/ha or more.

Causes of the legume effect

The measures made here of the soil nitrogen available to the wheat indicate a fairly small difference between the legacy from legumes and that from cereals (Tables 11, 15 and 23) and the yield benefit from the legume break was sizeable (Table 17). It is therefore surprising that achievable yield responses were larger after cereals than legumes (Table 19), indicating a larger need for fertiliser N. It might be expected that these two differences would cancel each other out. However, the finding is consistent with conclusions from other (multi-level) fertiliser experiments where the explanation appeared to be that, at the optimum nitrogen level, the 'effectiveness' of nitrogen taken up by the crop in generating dry matter (kg DM / kg N) was greater after a break crop than after a cereal (Vaidyanathan *et al.*, 1987).

It appears right to regard the nitrogen residue from legumes as 20-25 kg/ha rather than the 50-75 kg/ha that has previously been recommended (MAFF, 1988), and not to adjust the nitrogen requirement of the following wheat crop for the greater expected yield. However, there may be some difficulty in conveying to growers the need to discriminate between break crop effects and other field effects when, for the purposes of setting fertiliser applications, they assess yield expectations. The most pragmatic solution may be to persist with a belief in a large nitrogen residue and also the need for a yield adjustment, since the end result will be the same.

Measurements of soil mineral nitrogen are commonly used as the basis for fertiliser advice on the continent and increasingly the same is true in the UK. Even where they are not justified on a field by field basis, it is possible that they could be used to discriminate more closely between residues left in a range of common circumstances where full response experimentation would be laborious, for instance after irrigated and unirrigated potatoes, after linseed or after organic manures. It is therefore important to work out how it was possible to discriminate between the residues from peas and beans by measuring soil mineral nitrogen in the autumn (Table 11) but that this difference was apparently not maintained at harvest of the winter wheat crop.

Soil mineral nitrogen was a useful measure of soil supply since it accounted for 27% of the variation in yield response to nitrogen and 41% of the variation in the proportion of fertilised yield achieved with nil N. However, from the changes between measures of soil nitrogen supply, it appears that there were some significant differences in apparent net mineralisation over the season (Table 27), of which the change over-winter is given in Table 16.

'Net mineralisation' was apparently greater after peas than after wheat, and greater after beans than after peas. It was not possible to explain these differences on the basis of information collected on the size and nitrogen contents of the previous crops, or from the effects of previous crops on the dates of sowing of the wheat, but the differences are in line with the rates of mineralisation of legume residues reported by Fox *et al.*

(1990). Thus the differences between previous legume crops that were seen in autumn were not reflected in the responses seen at harvest. It would therefore seem necessary to continue with response experimentation in most circumstances, unless differences in the phasing of mineralisation can be ruled out.

Table 27. *Difference between grain nitrogen offtake without applied nitrogen (Table 23), adjusted to give total nitrogen uptake assuming a nitrogen harvest index of 0.75, and soil mineral nitrogen to 90 cm in autumn (Table 15). (kg/ha)*

		Previous crop :				
		CEREAL	*PEAS*	*BEANS*	*Mean*	*SED*
Season :	*1987-88*	17	31	37	28	
	1988-89	14	19	31	21	8.9 *
	1989-90	-6	-5	14	1	
	Mean	9	16	28		
	SED		3.7 ***			

It was expected that haulm, root and nodule residues from the legume crops would differ considerably amongst pea crops and amongst bean crops, and one objective here was to seek indices which might distinguish crops leaving small from those leaving large residues. There were indications that the farm estimated yields of beans related positively to soil residues measured in autumn. However, none of the information collected explained a statistically significant proportion of the variation in soil mineral nitrogen.

The nitrogen residues and enhanced health which follow legume break crops and which have been seen to influence the winter wheat crops studied here are just two of the many contributory factors which compose the web of environmental influence over the way wheat grows and responds to nitrogen. There is a need for a continuing and concerted programme which will gradually tease out an adequate understanding of the other factors which are of importance.

CONCLUSIONS

1. In seeking to improve the use of fertiliser nitrogen on winter wheat and other cereal crops the work reported here has indicated that spring sown peas and winter sown beans (some spring beans were included) leave a larger nitrogen residue than a previous cereal

crop (largely wheat here) but that the size of the residue is smaller than has previously been reported in the literature or has been indicated in fertiliser recommendations.

2. The residues from peas and beans were effectively the same but the residues from beans mineralised more slowly, so that soil mineral nitrogen analysis in autumn did not adequately detect the nitrogen that eventually became available.

3. Taking the effects of peas and beans on both the soil nitrogen supply and on yield into account, cereal growers acting on these results should apply about 25 kg/ha N less to winter wheat following a legume than to winter wheat following a cereal.

4. It appears that the relationship between crop performance of legumes (in terms of grain yield or nitrogen uptake) and the residue they leave is too complex to be explained from the records that are normally available on arable farms.

Acknowledgements

This paper is the final report on the experimental work funded by the H-GCA under Project No. 0023/1/87. Many thanks are due to Paul Boardman, Paul Flowers and Audra Hurst at Cambridge and staff at Wye, Kent who conducted the field work and analyses of data.

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NITROGEN LOSSES AND REQUIREMENTS IN ARABLE FARMING: THE NEED FOR NEW KNOWLEDGE

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SUMMARY

There are good reasons for the inadequacies in applying nitrogen to crops, but there is also good evidence of scope for improvements. For example, allowances for nitrogen residues from past cropping could be more accurate. Current investigations and recommendations aim to improve estimates of nitrogen residues and their retention. Losses by leaching could be reduced if nitrogen applications in autumn and applications to increase grain protein were discontinued and if reliable techniques for foliar application were developed and deployed. Formulation of effective new policies to restrict nitrate losses would be assisted by a better description of how husbandry, especially the use of fertilisers, affects crop yield and nitrate residues. However, the best hope of restricting nitrogen losses lies in better knowledge of the variation in and causes of the incomplete recovery of nitrogen applied to crops. Further research is needed before important questions can be answered.

INTRODUCTION

Nitrogen losses increase the need for nitrogen applications, and applications increase the risk of losses. Thus, nitrogen losses should be of crucial concern to arable farmers. However, farmers and their advisers take little account of nitrogen losses when applications are decided. Why? This paper summarises current philosophies for nitrogen application and then suggests (**suggestions are in bold**) what existing and new information might best assist in minimising nitrogen losses through changes in recommendations or legislation.

Current farm practices result from a combination of experience and advice. As a rule, advice is not changed without new evidence, normally from field

Fig 1 : An example of the effects of applied nitrogen on total costs and total returns from a crop of Winter Wheat yielding 7.3 t/ha at the optimum.

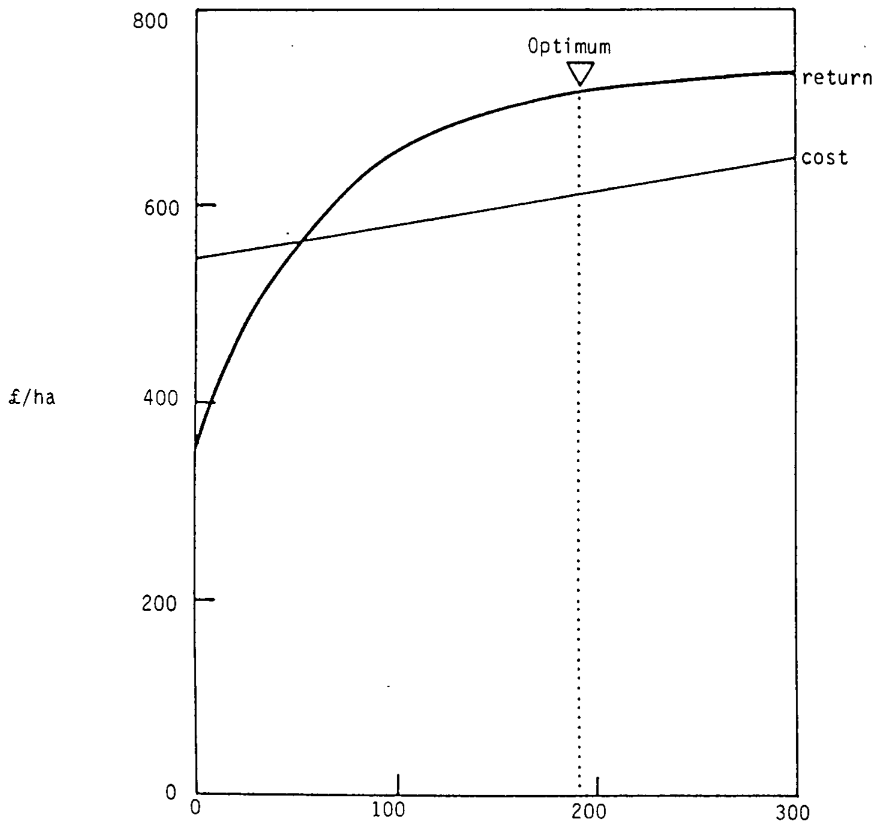
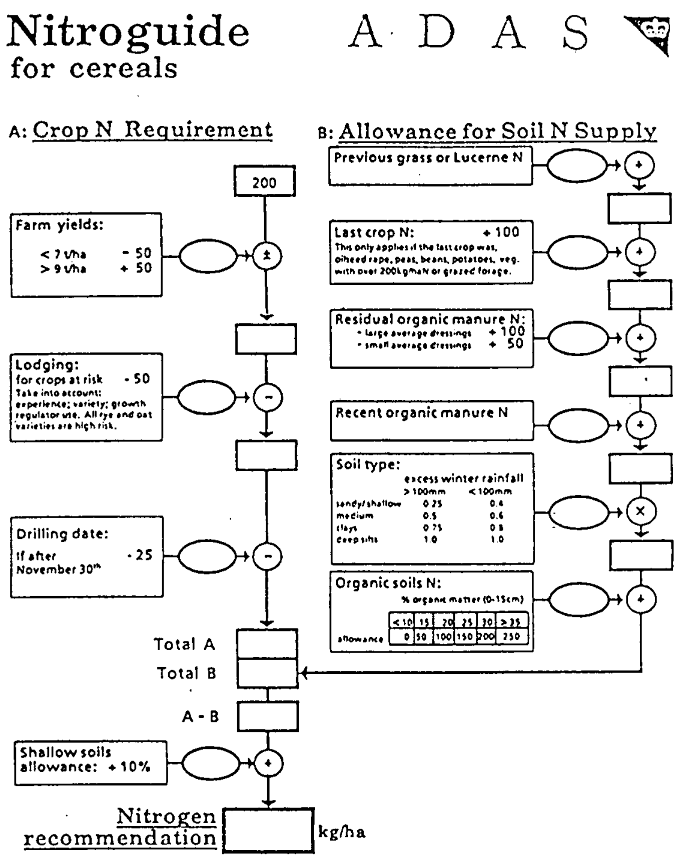


Fig 2. The nitrogen recommendation system introduced by ADAS in 1988 which gives the same or similar recommendations to those published in MAFF Reference Book 209, and cited in the Code of Good Agricultural Practice.



experiments. Thus, in order to improve advice, advisory agencies have conducted numerous experiments testing crop response to applied nitrogen. Whilst measuring the requirements of crops for nitrogen, information has also been gained of the nitrogen that crops remove from land and, more recently, the associated levels of nitrate and ammonium in soil. Thus, although nitrogen losses have seldom been measured directly, there is extensive existing data which describes the potential for nitrogen losses from land. Many of these data relate to land of moderate or high clay content but inferences can be drawn for land more prone to loss by leaching.

NITROGEN USE NOW

Crops can grow and yield without added nitrogen, relying solely on soil nitrogen. However, such practice is rarely profitable (except with legumes). Adding nitrogen causes a crop response which allows all costs to be covered, and more, hence profit (Fig. 1). The optimum quantity for profit from non-legumes can vary between zero and more than 300 kg/ha N. All agencies which give nitrogen advice explain the varying optima through the concept of a balance between crop 'requirement' for nitrogen and the 'supply' from soil and fertiliser. The relatively simple system used by ADAS for cereals is shown as an example in Fig. 2. The criteria used by other agencies (e.g. fertiliser manufacturers, advisers abroad) differ in detail but the concept is essentially the same. Soil supply is estimated according to previous cropping and organic manures applied. Losses of soil nitrogen are estimated according to soil type. In fields where there is a large uncertainty (large soil supplies could have a large effect on the optimum application) ADAS is piloting **a new service whereby available soil nitrogen can be measured.** (Where soil nitrogen supplies are thought to be moderate or small the cost of analysis has proved greater than the result of any improvement in the estimate (Fig.3)).

The amount of nitrogen 'required' (from soil and fertiliser) by cereals, oilseed rape and potatoes is adjusted according to expected level of yield and also, for cereals, according the intended quality of the grain.

The average amounts of nitrogen used by farmers to grow crops have, except for sugar beet, increased considerably over recent decades (Fig. 4) but use varies widely from field to field. The data do not allow a check of absolute amounts used in practice against amounts recommended (because yield levels have not been recorded in the Survey of Fertiliser Practice) but there are indications that **some advised adjustments (for example on the basis of previous cropping,** Table 1) **are not followed in practice.**

Fig 3 : Soil mineral N to 90 cm in autumn and optimum amount of applied nitrogen for Winter Wheat grown in England or Wales 1986-1987 in fields where organic manures had been applied (M. A. Shepherd personal communication).

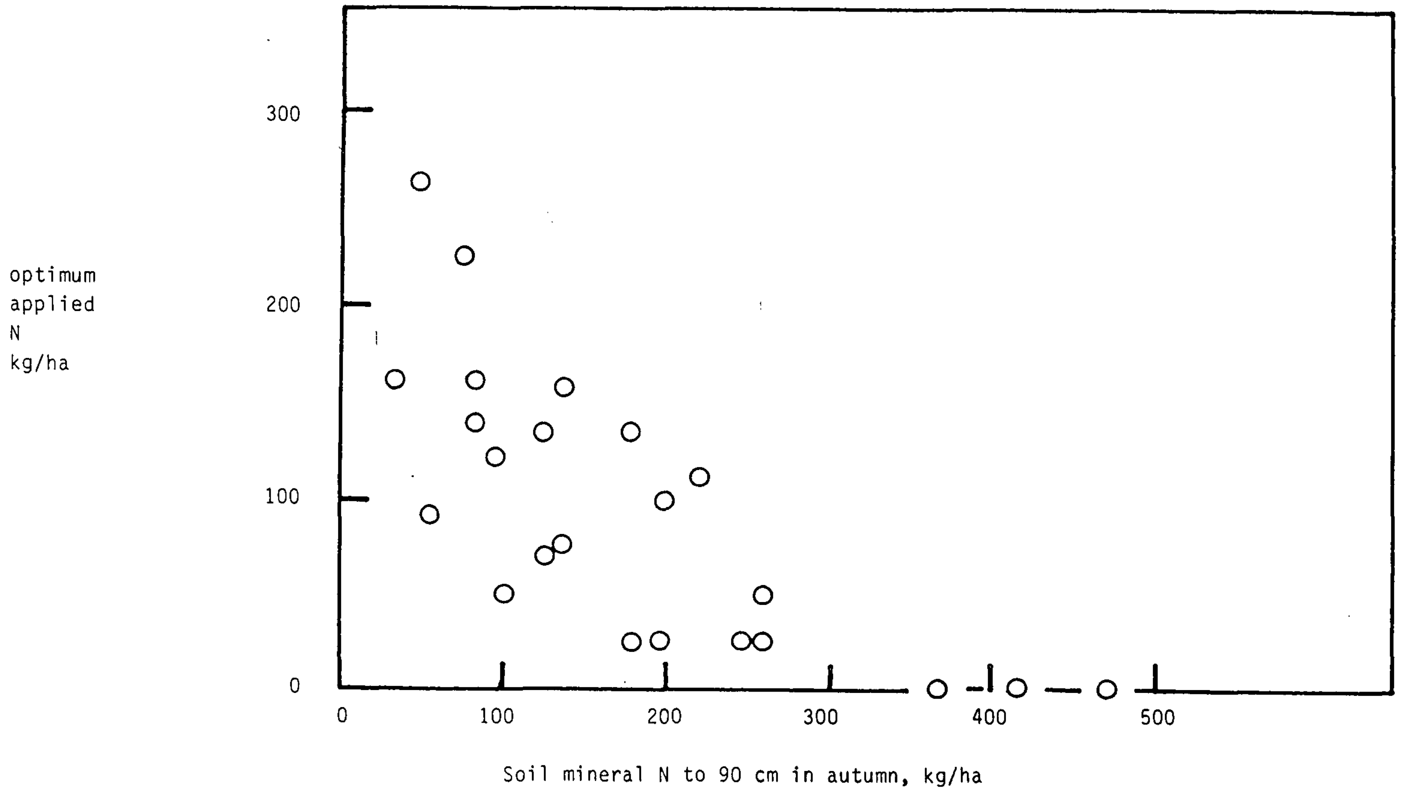
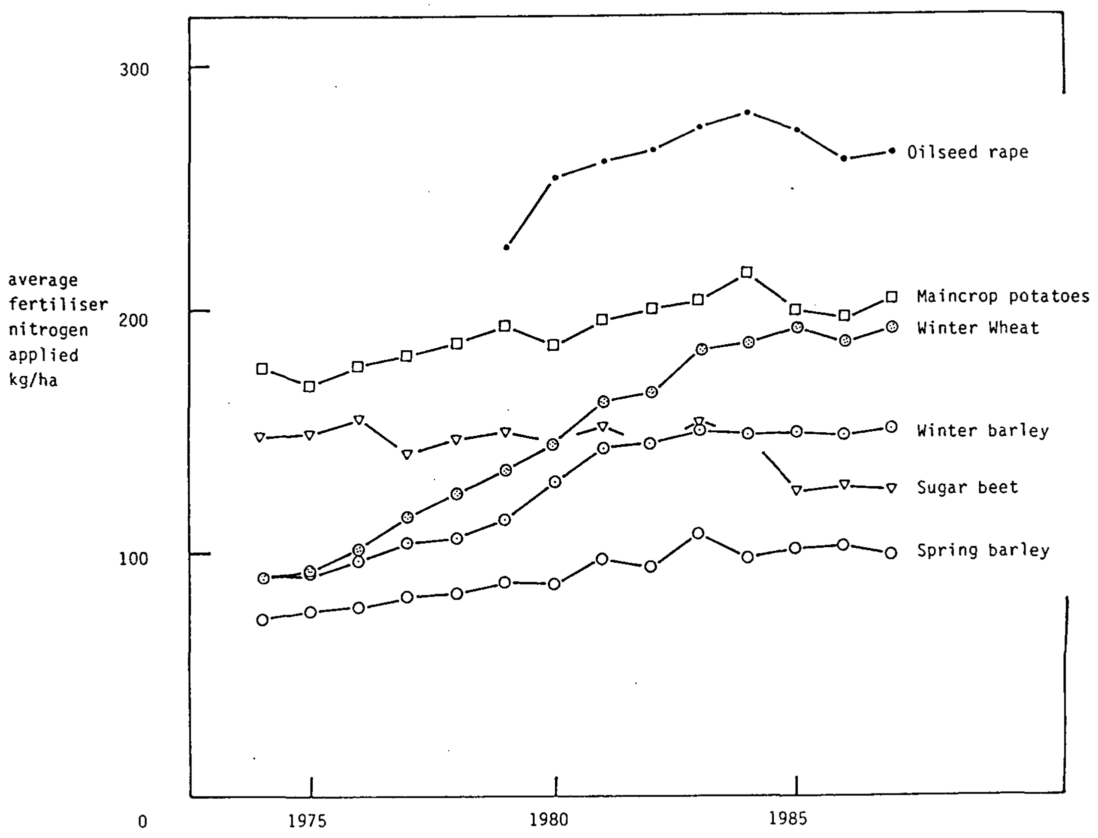


Fig 4 : Average annual use of fertiliser nitrogen on arable crops in England and Wales, 1974-1987 (Chalmers & Leech, 1988).



Table

Average total amounts of fertiliser N applied to major arable crops in England and Wales in 1984-6 according to the previous crop: cereals or sugar beet (N index 0), potatoes, beans, peas or oilseed rape (N index 1). (Survey of Fertiliser Practice, P.K.Leech, personal communication).

Crop	N Index 0	N Index 1	Difference actual	Difference recommended
	kg/ha N	kg/ha N		
Winter wheat	192	182	10	25-100
Winter barley	150	149	1	35-60
Spring barley	105	97	8	25-50
Oilseed rape	271	(263)	(8)	25

( ) = limited data

Fig 5 : An example of total crop nitrogen at harvest as it was affected by applications of nitrogen for a crop of Winter Wheat grown after a cereal in Essex, 1984. The 'apparent recovery' of the optimum amount is indicted (50%).

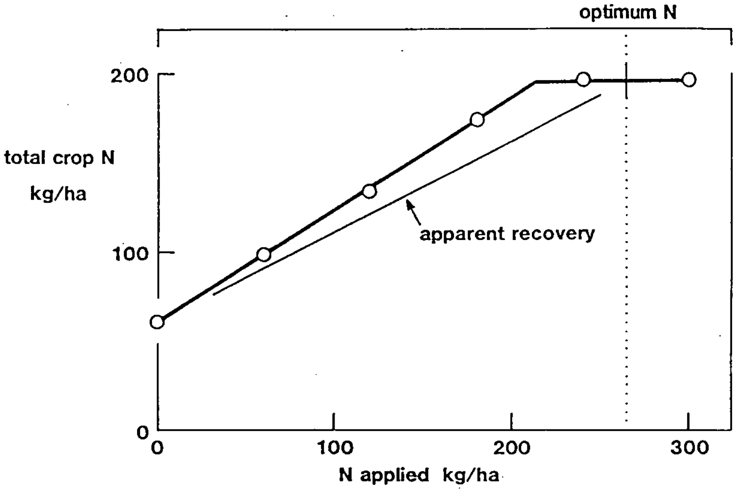
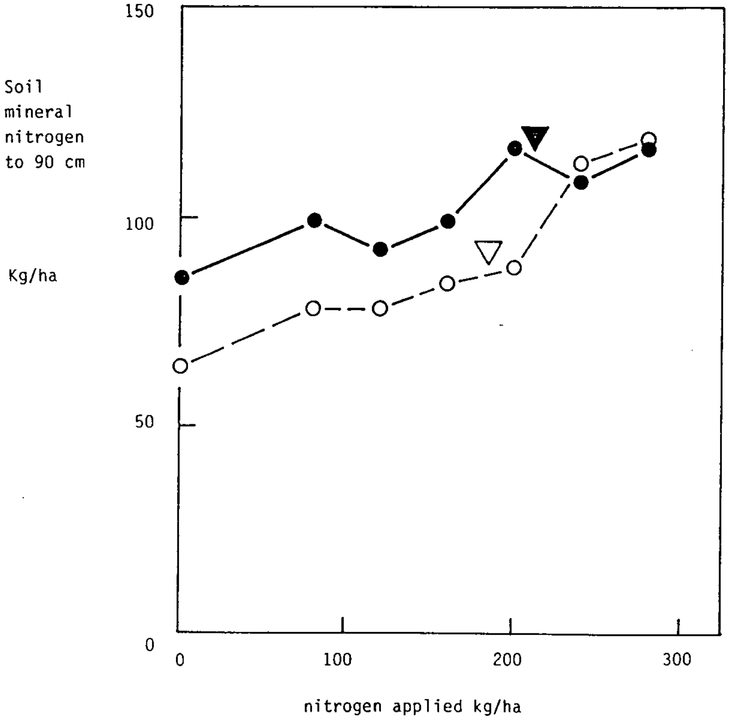


Fig 6 : Effects of nitrogen applied to Winter Wheat (open circles) and oilseed rape (closed circles) on soil mineral nitrogen to 90 cm during winter under the following wehat crop. The two experiments were at separate sites with clay soils in Essex, 1986-87. Arrows indicate amounts of applied nitrogen which had been optimum for profit.



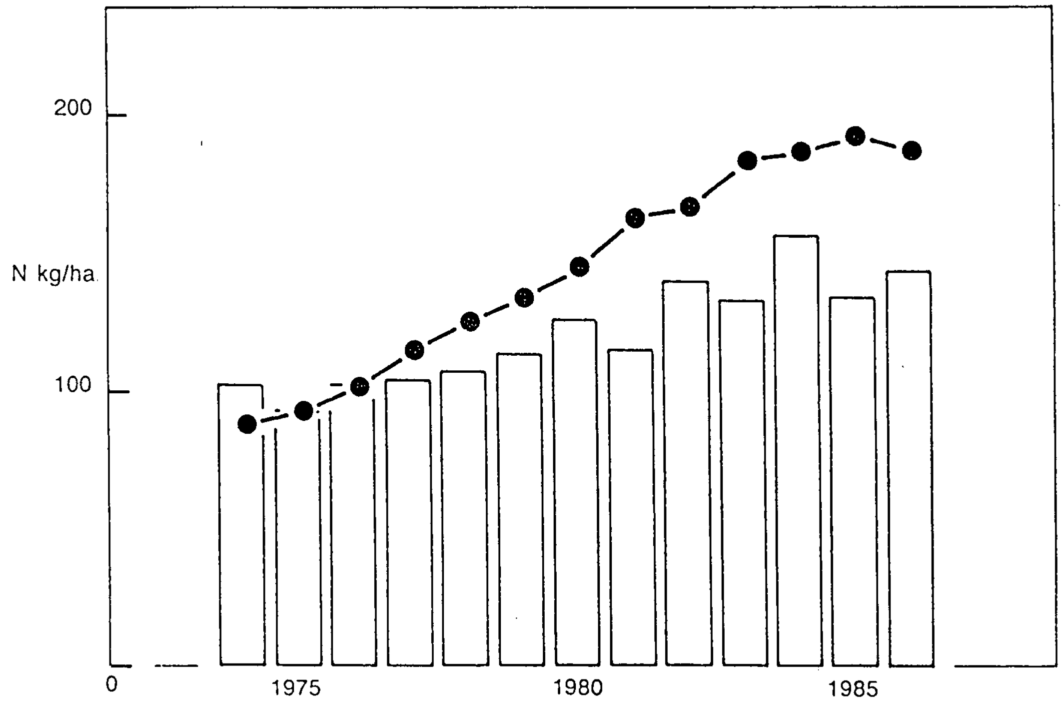
However, advice is imperfect: experiments show that much of the variation in economic optimum amounts of applied nitrogen is not accounted for by the factors used to adjust advice. Some of this variation will always be unpredictable because it arises from events occurring after the time at which nitrogen must be applied.

NITROGEN RECOVERY NOW

The change in crop nitrogen content resulting from an application of nitrogen is a measure of (net) recovery. In a recent series of 70 experiments on winter wheat grown on clay soils in East Anglia between 1981 and 1986 the "apparent" recovery of the optimum amount varied between 43 and 88% (Bloom et al, 1988). Little of this wide variation could be explained and **no concept to explain the differences in recovery has so far achieved acceptance amongst advisory agencies.** However, recovery should be predictable because in most individual cases the proportion of applied nitrogen recovered was consistent over a range of amounts applied; only as the amount increased to approach or exceed the optimum did recovery diminish (Fig. 5) ie there is a site-specific effect. In a review of a further 58 experiments examining grain protein concentration in winter wheat it was calculated that, of nitrogen applied extra to that recommended for yield, an average of only 9 out of 50 kg/ha was accounted for as extra grain protein (Sylvester-Bradley & George, 1987). This worse 'recovery' where larger amounts of nitrogen have been applied appears to be reflected in disproportionately larger residues of soil mineral nitrogen during the following autumn or spring (Fig. 6). In the few tests made so far of the effects of applied nitrogen on the next crop there have been apparent recoveries of nil to 20% (of nitrogen applied for the previous crop) (Vaidyanathan, personal communication). **Crops which (apparently) recovered nitrogen from applications in a previous year show their own optimum amount to have been reduced.**

Recovery of nitrogen from soil, previous crops, manures and fertilisers partially or fully compensates for incomplete recovery of current nitrogen applications. Thus modern arable farming does not necessarily increase risk of nitrogen loss. Depletion of soil nitrogen (and reduced risk of nitrogen loss) usually occurs in fields where cereals or sugar beet follow legumes, potatoes or oilseed rape, provided fresh applications are tailored to take account of the residues. On the other hand soil nitrogen is enhanced (and with it the risk of loss) following these latter crops and also with cereals, where soil supplies are underestimated or crop requirement overestimated. For winter wheat the increased use of fertiliser nitrogen over the past decade

Fig 7 : Estimates of average amounts of nitrogen applied to (circles) and removed by Winter Wheat crops at harvest (columns) for England and Wales according to census and survey data.



appears (from national statistics, Fig. 7) not to have been balanced by an equivalent increase in nitrogen removal by the crop. It can thus be argued that continuous cropping with winter wheat now leads to an increase in soil nitrogen status (and an increase in risk of nitrogen loss). **There is a need** to check this and **assess the impact of smaller nitrogen inputs on fertility and profit in the medium term.**

IMPROVED NITROGEN ADVICE

At present advice is accepted on the understanding that it assists the commercial objectives of the farmer. If arable methods and agricultural laws do not change, reduced risk of nitrogen losses from land can only come from reducing either the extent to which a farmer underestimates soil nitrogen supplies or the extent to which he overestimates crop nitrogen requirements.

The current simple **systems of 'nitrogen prediction'** (e.g. Fig. 2) **have ample scope for improvement** and sophistication. Evidence for improved estimates of soil nitrogen supply is being sought through current experiments and new research proposals. These should allow:

* **better estimates of residues from grass on the basis of ley duration and nitrogen applied.**

* **residues from legumes to be differentiated on the basis of species and crop size.**

* **residues from recent organic manures to be judged according to times of application, soil incorporation, and drilling.**

* **residues from cereals, oilseed rape and potatoes to be assessed according to yield achieved and nitrogen applied.**

* **overwinter retention of mineralised nitrogen to be assessed according to soil series, rainfall and measurements at reference sites.**

* **summer mineralisation of nitrogen in organic soils to be estimated according to organic matter content and summer rainfall.**

The potential of experimentation on soil nitrogen supplies has been enhanced by the development of an ability to make extensive measurements of mineral nitrogen in the soils and the demonstration that such measurements can relate well to crop uptake of soil nitrogen.

Improvement in the estimation of crop nitrogen requirements has proved a more intractable objective. Although a link between crop yield, crop nitrogen content and crop nitrogen requirement may appear axiomatic and, although this link is recognised by most nitrogen recommendation systems, the relation between crop yield and crop nitrogen requirements as determined by experiment is weak, and the predictable differences in yield (such as those due to site) are small compared to the unpredictable effects (such as those due to season). As a result it was concluded for a series of 104 experiments on winter wheat in East Anglia that a prediction of yield would not have improved the economic performance of any nitrogen recommendation system (Sylvester-Bradley et al, 1987). This surprising result was partially explained by the tendency for high yielding crops to recover a greater proportion of the applied (and possibly also the soil) nitrogen (Bloom et al, 1988), but it was also due to unexplained variations in recovery, harvest index and crop nitrogen concentration.

Progress in the estimation of crop nitrogen requirement must therefore depend on parallel investigations into variation in yield, nitrogen concentration and nitrogen recovery. The principal factors responsible for variations viz. soil type and microbial activity, root and stem-base diseases, lodging, weed competition, soil moisture, and meteorological conditions are not all amenable to control in experiments. **The most promising way forward must** therefore **be through carefully structured and carefully monitored series of inter-site comparisons in successive seasons.**

IMPROVED NITROGEN RECOVERY

If recovery of applied nitrogen were complete, arable farming could only cause nitrogen losses indirectly (eg by increasing turnover of soil nitrogen), and any uptake or immobilisation of soil nitrogen would diminish the chances for loss. As has been shown, recovery of applied nitrogen is not complete so improvement in recovery is a worthwhile objective from an environmental (and also a commercial) point of view. However, whilst ideas for improving nitrogen recovery may be seen as effective, their adoption depends either on the benefit exceeding costs, on adequate financial compensation, or on coercion. Investigations must thus include financial assessments.

Soil nitrogen: Nitrogen losses are larger from soil than from crops and so must be minimised by restricting the time that loss-prone forms are in the soil. Soil mineral nitrogen tends to be minimal as crops are harvested but substantial mineralisation of organic nitrogen occurs as warm soils are disturbed and re-wetted in autumn. Thus **the following ways of minimising nitrogen losses from soil are or should be subjects of investigation:**

- **delaying harvest**
- **minimising or delaying subsoiling, cultivation or other soil disturbances**
- **controlling draining or moling.**
- **straw incorporation**
- **microbial inhibition**
- **early drilling of autumn-sown crops**
- **catch cropping before spring-sown crops**

Such 'restrictive' practices are most likely to be economic where residues are large, for example where land in leys is to become arable or where animal manures have been applied. It should be noted that component practices of 'organic' farming systems do not appear compatible with the restriction of nitrogen losses because they tend to depend on animal manures for nutrients and on repeated cultivations and later drilling for weed control.

Fertiliser nitrogen: The lack of understanding of the wide variation in recovery of applied nitrogen is a major obstacle to devising ways for its improvement. Although the interactions between applied nitrogen and soil micro-flora can be minimised by timing applications to coincide with crop uptake (e.g. by discontinuing autumn nitrogen applications), they cannot be avoided entirely if fertiliser has to be applied to soil. There are indications from recent experiments (Bland & Lord, 1988) that some applications can cause sufficient **unexpected immobilisation or enhanced mineralisation** to markedly affect the quantities of nitrogen available for crop uptake in the short term. **An understanding of these effects might lead to an improved rationale for timing nitrogen applications to soil and improved recovery.**

Fig 8 : Grain 'protein' concentrations calculated as at point of sale from near infrared refluctance (NIR) and loaf volume from the long fermentation baking process (LFBP) determined by the Flour Millers and Bakers Research Association for milling wheat crops grown at sites throughout England and Wales in 1985 (circles) and 1986 (squares) with just the nitrogen recommended for a grain yield of 7-9 t/ha.

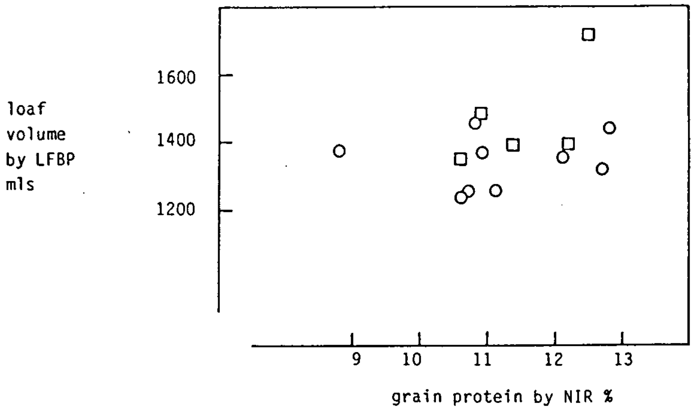
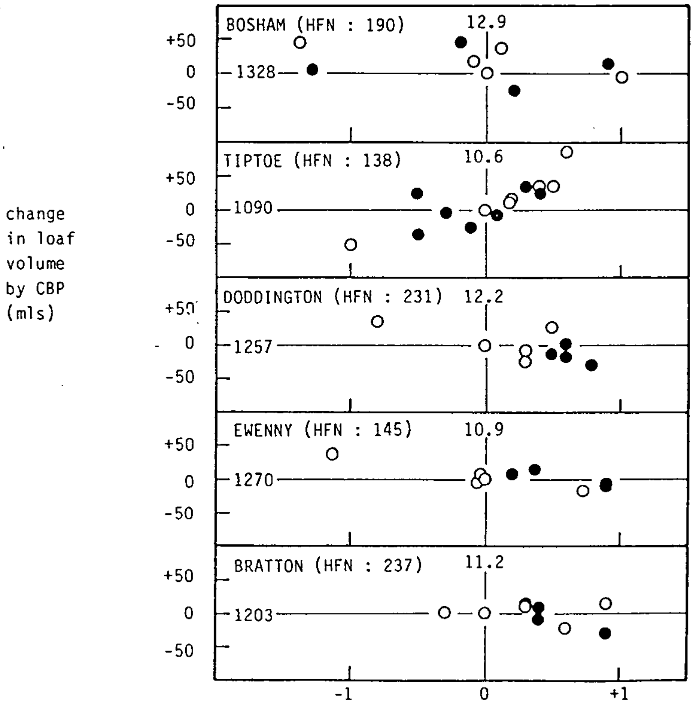


Fig 9 : Changes in grain protein concentration calculated as at point of sale from near infra red refluctance (NIR) and loaf volume from the Chorleywood baking process (CBP) determined by the Flour Milling and Baking Research Association due to nitrogen applications excluding (open circles) or including (closed circles) urea sprays. Effects are due to treatments which differed in timing or amount from the N recommended for a grain yield of 7-9 t/ha. Experiments are those indicated by squares in Fig. 8. Hagberg Falling Number (HFN), grain protein concentration and loaf volume are given for the recommended nitrogen treatment at each site.



Interactions of applied nitrogen with soil processes might be avoided if nitrogen was applied to and directly absorbed by leaves. Sprays of urea solutions have been used commercially for many years, principally to increase grain protein concentrations (sometimes as a fungicide). Recovery of sprayed nitrogen can on occasion be near complete but is, on average, poor; recent (unfinished) direct comparisons (Vaidyanathan, personal communication) have shown little difference in recovery between **sprayed urea** and soil applied ammonium nitrate but **it is possible that formulations or application techniques could be devised to improve recovery.**

Losses of the nitrogen taken up by crops are rarely measured. Net losses from crop canopies are unlikely in growing crops where uptake is rapid and would be difficult to detect in static or dormant crops because precision of measurement is poor. However, recent isolated observations using N-15 (Schorring et al, 1987; Smith et al, 1984) and micrometeorological techniques (Harper et al, 1987; Lemon & van Houtte, 1980) indicate that **gaseous losses of ammonia from crops** cannot be ignored and **should be measured for modern arable conditions.**

The most thoroughly substantiated conditions for poor recovery of fertiliser nitrogen are where super-optimal amounts are applied. Such applications are commonplace where wheat is grown for the breadmaking market because millers demand a high protein concentration in the grain. However, the tradition of basing a sale on protein content now appears unnecessary since modern baking techniques are insensitive to protein level (Fig. 8), recent experiments show protein levels to be adequate for breadmaking with only the amount of nitrogen recommended for optimum yield (Fig. 9) and if grists are found to be deficient in protein they can be fortified with extracted gluten. **Further experiments may be necessary to convince the industry that grain protein screening and super-optimal nitrogen applications can be discontinued.**

CONCLUSIONS AND FORMULATION OF POLICY

The research and development employed over the past decade to support the arable farming industry has accumulated **the wealth of existing information** which **can** also **be used to assess risks and devise means of minimising nitrogen losses from land.** Future investment in research on this topic must aim to exploit (by reprocessing) this valuable legacy as well as by mounting new investigations.

The prediction of nitrate leaching from land seems likely to be a policy requirement for the foreseeable future. Models are needed to operate on a catchment, farm or field basis. Global information will be of little help in advising an individual farmer on his particular course of action. We should therefore look to build models from a field scale.

Models are required to answer two rather different questions:

1. What will be the effect of changes in agronomic practices?

2. What changes are necessary to produce a given effect?

In the first case there is one answer, albeit subject to confidence limits. In the second there may be a number of alternatives which justify subsequent economic appraisal.

To date policy considerations have been based on the WRC model (Oakes, 1982) which assumes that nitrate leached is a constant proportion of fertiliser nitrogen used irrespective of:

- soil type or drainage status
- differences in rainfall and other weather changes
- differences in husbandry.

These limitations are recognised by those involved. There is particular concern that both theory and soil mineral nitrogen data (Fig. 6) indicate that **losses are likely in the absence of fertiliser use and that a curvi-linear relationship is more appropriate. Further use of the model will require at least a better representation of this relationship.** Such a revision should be possible for cereals on the basis of existing data. What is less clear is how far revision would be possible for other major arable crops or grassland, and whether modifications are possible to account for those cultural, edaphic and climatic factors known to affect accumulation and loss of mineral nitrogen.

A realistic assessment is required of how far and how fast we can proceed.

ACKNOWLEDGEMENTS

Many of the conclusions made from ADAS data result from intensive support by the Statistics Department at Rothamsted. The preparation of this paper depended heavily on material prepared under H-GCA Grant 0023/1/87.

This paper was initially presented as a MAFF Special Topic Review. The HGCA and the author are grateful to the Ministry for permission to publish the paper in this HGCA Project Report.

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H-GCA RESEARCH REVIEW No. 18

PHYSIOLOGY IN THE PRODUCTION AND IMPROVEMENT OF CEREALS

Report of a working group written by
R. SYLVESTER-BRADLEY & R.K. SCOTT
with C.E. Wright as technical secretary

ABSTRACT

Background

1. This report focuses on the context in which decisions are taken during cereal production, and analyses the part that physiology can play in influencing those decisions. Using this approach we have identified the aspects of physiology on which more study has a good chance of improving production.

2. Before writing the report we took evidence, particularly about the views of the end users, and an initial working group of cereal physiologists was augmented with expertise on specific issues where necessary.

3. At the start, we set out the points of physiology on which there was general agreement and which could be seen as pertinent to the production of cereals (Chapter 2). Thus we begin by summarising the physiology relating to roots, leaves, tillers, ears and grains, but only identifying the points on which choices may turn in practice.

4. The most crucial element in the interpretation of cereal physiology is that aging (development) and growth should be perceived as independent processes.

   In analysing the potential for cereal production (Section 3.9, page 92), the extent to which potential is achieved clearly reveals much scope for improvement. The ranges in wheat performance from 6.4 to 8.6 t/ha over seasons in the 1980s and 6.2 to 8.2 t/ha between experimental husbandry farms of ADAS demonstrates the huge influence that environment has over performance. The exceptional performances at all sites in 1984 and over all seasons at Rosemaund EHF can both be attributed at least in part to **slow development with fast growth.** Hence, in making decisions crop by crop we can assert that growers should set their sights on both speeding growth and prolonging development.

5. Unfortunately the current disposition of institutions researching on crops too often allows their scientists to ignore that good decision-making must depend upon the combined forces of deduction and experience; the laboratory-based physiologist assumes that decisions must all be made by deduction whilst the field-based agronomist takes it for granted that all he can do is 'suck it and see'.

6. Our concern in the body of the report has therefore been to juxtapose the approaches of the physiologist and agronomist, so that the agronomist is reminded of the relevant physiology and the physiologist can see the relevant agronomy (Chapter 3). We contend that to provide for profitable decision-taking both influences should be harnessed; agronomic experience sets the limits within which a practice can sensibly be altered and, when relevant agronomic experience is deficient, physiological knowledge provides the means to reason how adjustments should be made.

7. Paradoxically, agronomic experience is becoming increasingly deficient. This is because of the ever more complex constraints under which growers have to work with the ever shrinking support for work on new developments. Thus, the industry will increasingly rely upon knowledge of crop function to decide what course to take at each stage in the production process.

Recommendations

8. Having consulted physiologists worldwide we have considered the requirements of breeders and biotechnologists (Section 3.10, page 103; Section 3.11, page 110) and identified opportunities for research in their support. However, we deliberately avoid saying that new funding of physiology should concentrate on preparing the ground for the genetic manipulator; the excitement that the new prospects have engendered guarantees investment without the assistance of levy funds.

9. That **choice of variety** (Section 3.2, page 28) is of consuming interest to growers is understandable; that this interest finds vent in so many uncoordinated trials is not. There is clear scope for coordinating official and private trials of varieties and amalgamating their results in order to improve the precision of the tests being made and the chance of fitting varieties to circumstances. Inclusion of meaningful agronomic characters when

distinguishing varieties would also help towards this end (Section 4.4.1, page 118).

10. The normal compromises struck in **date and rate of sowing** (Section 3.3, page 34) appear to leave unrealised much potential for growth and yield. With economic and other restrictions on the use of nutrients and pesticides the need is to fully harness any environmental strengths. We see some scope to explore and overcome the physiological obstacles which negate the benefit from intercepting extra light energy and nitrogen through early sowing and denser stands (Section 4.4.2, page 123).

11. With **weed control** (Section 3.5, page 57), stringent use of herbicides is the crucial object. To this end we endorse existing and new work on predicting the weed seed burden, determining weed thresholds for crop loss, determining how either crop or weed may tolerate chemical sprays, and determining the principles governing spray application techniques.

12. Looking in the same way at current strategies for **disease control** (Section 3.6, page 65) there appears scope for improvement through research into disease effects at different stages of crop development, especially on the main yield-forming leaves (Section 4.4.4, page 130), and direct effects of fungicides on crop growth.

13. Environmental repercussions of **nitrogen** (Section 3.4, page 44) now mean that, without the support of industry, more attention will be paid to the nitrogen left behind by cereals than to nitrogen forming the grain. Our view is that, given adequate techniques, cereals could be fertilised more effectively if the aim were to optimise canopy development rather than to supply a 'requirement' guessed at an early stage. Complementary research should focus on work to maximise recovery of applied N, to examine more precisely the relationship between N requirement and yield, to define how N can be used to modify the canopy for maximum crop growth, to develop the potential of foliar applied nitrogen (Section 4.4.3, page 126), and to deduce the optimum pattern of N application to conform with the needs of the malting and baking industries.

14. Both the recognition and restriction of **lodging risk** (Section 3.7, page 73) need close analysis (Section 4.4.5, page 133), particularly with winter barley, because so often lodging is what governs the benefit for both yield and

quality from decisions on nitrogen, as well as early sowing, seed rate change, and crop protection measures.

15. The grower is constantly exhorted to produce **high quality grain** (Section 3.8, page 80), and yet so often quality defies control. We assert (Section 4.4.6, page 135) that there is much existing physiological knowledge which could be used by the grower during those few crucial weeks, providing up-to-the-minute intelligence on which to monitor (and maybe mediate) the success of grain-filling as it unfolds, and focus his expectations. Quick and reliable tests must be developed for use, not only at the point of trade, but on the farm, to determine levels of germination, protein concentration, alpha-amylase and grain size characteristics.

16. It is woeful and perplexing that the industry can reach the penultimate stage in the long production process with little advance knowledge of its success. Intelligence for merchants, traders, processors and end users, let alone growers, of both the volume and the quality of grain that they are to handle is surprisingly weak until harvest is under way. It is high time that cereal physiologists addressed this conundrum (Section 4.4.7, page 138), not with the promise of perfect foresight, but to state the narrowing probabilities as growth proceeds.

17. Underlying all assertions in our Report rests a recurring reference to 'the model'. It is both undesirable and unfortunate that 'modelling' has been allowed to assume a mystique which alienates the layman (Section 4.2, page 114). Without doubt we are all modellers in our different ways; our thoughts on crops **are** models and modelling is at the root of communication in crop science. We therefore make no apology for homing in on models as the cornerstone of crop improvement programmes. We do not claim that they offer quick solutions, or a direct route to the laws of nature, but we do assert that, for what has been allowed to remain a most inexact science, recorded models can confer a common and beneficial discipline and provide that all-important access to physiological know-how.

18. With the many opportunities for physiological research identified in this summary and those others given in the full report (there is a list on page 116) we recognise the need to devise a strategy which will most effectively exploit resources limited in terms of finances and skilled staff. There are some projects which are not appropriate for extensive collaborative teams,

for instance the study of the origins of high amylase grain or of predicting dormancy. There are others for which a multidisciplinary approach seems essential, both for economy and synergy. An example is that in devising a technology for uptake of nitrogen through leaves, parts should obviously be played by the spray engineers, plant biochemists, formulation chemists and soil scientists, as well as by physiologists who can determine the N needed for growth.

19. However, in developing solutions to its fundamental problems, there is another synergism to be found, through harnessing more disparate interests in the industry. It becomes clear that **it would be of benefit if the industry were to become involved in the execution of research projects.** We therefore advocate that concerted programmes are constructed which allow cross communication through the grower-adviser-supplier-journalist-scientist chain of intelligence by forging specific partnerships which hold a focus on the problems in practice. We have looked at research needs, identifying areas where a 'vertical' collaborative stratagem could be used to good effect.

For instance:

a) Anticipation of crop performance during growth depends on the interest of growers and traders, and rapid communication through journalists, as well as the work of physiologists.

b) When analysing elements of the risk of lodging, observations must be garnered not only from agronomic experiments, but from specialists in structures, growers and advisers.

c) The integration of concepts of how leaf diseases affect yield needs epidemiologists, physiologists and meteorologists and holds a close interest for fungicide manufacturers.

20. If the admirable integration that the Authority has established on a horizontal plane between researchers were complemented by such a **vertical integration linking science through physiology to practice**, benefits would accrue to the industry on a scale far exceeding those which come from piecemeal funding of isolated projects.

This review, completed in January 1990 and with 156 pages in the full article, was funded by the HOME-GROWN CEREALS AUTHORITY, Hamlyn House, Highgate Hill, London N19 5PR.

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