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FOLIAR-APPLIED NITROGEN FOR GRAIN PROTEIN AND CANOPY MANAGEMENT OF WHEAT

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FOLIAR-APPLIED NITROGEN FOR GRAIN PROTEIN AND CANOPY MANAGEMENT OF WHEAT

By

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Abstract

This review was undertaken to investigate the efficiency of crop capture and recovery of foliar-applied nitrogen (foliar N), assess effects on the crop and the factors influencing the occurrence of crop damage, and review where the industry might benefit from further research and development.

Grain protein levels have shown a tendency to decline in recent years. The advent of high-yielding cultivars with bread-making potential may have exacerbated the problem. Application of foliar N late in the season is the most efficient method of boosting grain protein, but UK growers favour the use of granular N applied earlier in the season, as yield responses are more likely, and there is a risk of leaf scorch with urea N. Yield responses to late season foliar N are more likely where previous soil-applied nitrogen is sub-optimal and where foliar N is applied prior to anthesis. Foliar N applied close to ear emergence can delay leaf senescence, prolonging photosynthesis for about 7 days. The optimum application timing to boost grain protein is typically between anthesis (GS 60-69) and grain milk development (GS 70-79). The extra protein derived appears to be of a similar quality to that obtained from soil-applied nitrogen. The response in grain protein is of the order of 0.8% per 30 kg ha^{-1} N applied.

Typically 60-70% of the foliar N spray is intercepted by the crop canopy. A significant proportion of the applied spray is deposited on the soil surface. Up to 65-70% of foliar N is usually recovered in the crop, similar to values for soil-applied N, though less nitrogen in total appears to be retained in the soil-crop system at harvest. Loss pathways for foliar N do not appear to be fully characterised, leading to a number of assumptions regarding the loss of foliar N from the crop, soil and plant system. Around 10% of the urea-N applied can be ‘lost’ via volatilisation of ammonia, compared to 0.8% for ammonium nitrate. Adjuvants can increase uptake of foliar N, but with the risk of increasing leaf scorch. The exact cause of scorch is not clear. Accumulation of urea, ammonium or other interim products of protein synthesis appear to be the most plausible cause. Where scorch does occur, damage can typically affect up to 10% of the sprayed leaves at typical field application rates of 40-60 kg ha^{-1} N.

In the future, to meet the demands of high yield and grain protein, without increasing lodging or disease risks, more N is likely to be required later in the season especially if retention and crop utilisation can be improved and the problems of scorch overcome or reduced.

A number of areas for further work and development were identified:

1. Development of methods for grain protein prediction.
2. Nitrogen strategies for high yielding milling wheat.
3. Improving crop utilisation of foliar N and minimising the risk of scorch.
4. Studies of wheat with modified rates of urease or glutamine synthetase activity to improve understanding of foliar N loss pathways and the causes of scorch damage.

1.0. Introduction

Late foliar N for grain protein concentration

According to National Association of British and Irish Millers (NABIM) figures, the UK bread-making industry requires around 5.5 million tonnes of wheat each year. Around 80% of this demand is met by UK produced wheat, though this figure varies considerably from year to year depending on grain quality. Currently close to one third of the UK winter wheat area is cropped with varieties suitable for milling (Grade I and II cultivars) (Chalmers *et al.*, 2000).

Between 1995 and 1999, wheat grown for milling markets received on average 16 kg ha^{-1} more nitrogen than wheat grown for feed and other non-milling uses (Chalmers *et al.*, 2000). This additional N is applied in an attempt to boost grain protein concentration. According to the UK Survey of Fertiliser Practice, between 1995 and 1999, wheat for bread-making markets received an average of 202 kg ha^{-1} N, and for non-milling markets 186 kg ha^{-1} N (Chalmers *et al.* 2000). However, more detailed examination of the data from this survey indicates that only around 45% of all milling wheat received extra nitrogen (on average 45 kg ha^{-1} N), and of these only 17% of crops are treated with a late foliar N spray (A. Chalmers, personal communication). Along with grain specific weight and Hagberg Falling Number (which provides an indication of grain alpha-amylase levels), grain protein concentration is a key determinant of the marketability of grain with bread-making potential. Typically, a minimum grain protein content of 13.0 % (100% DM basis[1] (equivalent to 11.0 % @ 86% DM)) is required to obtain a milling quality price premium. In the UK, foliar N as urea (46% N) is often applied late in the season in an attempt to boost grain protein content. As the yield of bread-making cultivars increases through breeding, competition for nitrogen within the plant means that grain protein content can be ‘diluted’, and consistently achieving such high grain protein levels on high yielding sites can be difficult (Clare *et al*., 1993).

Trends in grain protein concentration

In recent years nitrogen application rates have stabilised for both economic and environmental reasons, while wheat yields have continued to rise (Figure 1A) due to improved varieties and management techniques. This is affecting average UK grain nitrogen content (which is directly related to grain protein content) which demonstrates a declining trend in recent years (Figure 1B). As higher yielding cultivars with bread-making qualities are developed (e.g. Malacca, Shamrock, Xi 19), this is likely to become an increasing problem. The economic realities of increasing nitrogen fertiliser price without matching increases in grain prices has reduced recommended nitrogen rates, and this is also placing downward pressure on protein concentration. Late-season application of foliar N potentially offers a means to counter-

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[1] Until recently, grain protein content was expressed on an 86% DM basis, based on Kjeldahl analysis. The new standard method (Dumas) expresses results on a 100% DM basis. All grain protein contents presented in this review are

balance this effect by allowing better targeting of N applications in relation to crop demand.

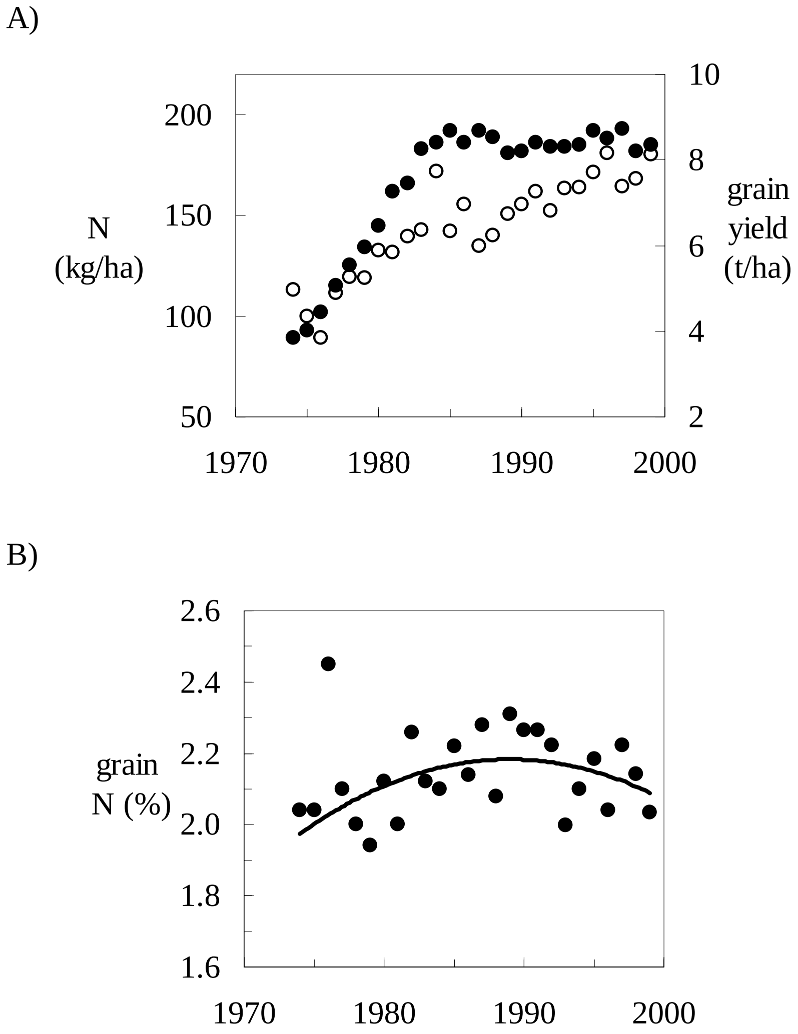

Figure 1. A) Trends in nitrogen fertiliser use on winter wheat (filled points) and average wheat yields (open points) during the period 1974-1999 (fertiliser data taken from the Survey of Fertiliser Practice (England and Wales), yield data taken from MAFF estimates of UK Cereal Production). B) Trends in grain nitrogen content over the same period (R^2 = 0.29) (data taken from the HGCA grain quality survey (mean of all varieties)).

Foliar N for canopy management

One problem facing the industry is that of maximising the efficiency of fertiliser use by crops to reduce N

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expressed on a total dry matter basis, and where necessary have been converted from data reported at 86% DM.

losses. Targeting nitrogen applications strategically in response to crop growth, and any difficulties encountered during crop development (e.g. poor rooting or dry soil conditions) is seen as means by which nitrogen could be used more efficiently in crop nutrition. Foliar N application would be a key tool in such strategies. Recent MAFF and HGCA-funded research work (Stokes *et al*., 1998) has investigated the concept of ‘canopy management’ to optimise the efficiency of fertiliser nitrogen use for grain production on a site-specific basis. By this method, nitrogen, at least in part, is applied judiciously in response to canopy growth and expansion, while at the same time minimising nitrogen residues in soil and the potential for leaching loss. Foliar N can be used to assist in the manipulation of crop canopies to attain optimal green area indices, given that there is a demonstrable relationship between crop nitrogen uptake and canopy expansion (Sylvester-Bradley *et al*., 1990a, 1990b). The advantage of using foliar applied nitrogen is that it is capable of being used as a tool to manage crop canopies during potentially dry periods of the growing season, when nitrogen uptake from soils is limited. Foliar nitogen may also be beneficial in situations where rooting is restricted and nitrogen uptake is adversely affected, for example in 2nd wheats affected by take-all (*Gaeumannomyces graminis*) infection of roots. Foliar N can also improve the scope for tactical adjustment of nitrogen nutrition, by allowing the period for decisions on nitrogen application rates and timings to be extended.

The anticipated advantages of using foliar N are that it by-passes the soil/root system thereby minimising the risks and uncertainty of nitrogen immobilisation by soil organic matter, and losses associated with denitrification and leaching (Poulton *et al.*, 1990). However, this needs to be balanced against increased losses by volatilisation of ammonia into the atmosphere. Foliar application also means that crop uptake of nitrogen is less dependent on soil moisture conditions (Dampney and Salmon, 1990). Late season application is particularly beneficial for boosting grain protein, a period when soil moisture can be limiting to crop nitrogen uptake from soil. By allowing delayed N application, foliar N application can also reduce lodging risk (Dampney and Salmon, 1990).

This review

From the above, it is clear that there are a number of areas where foliar N could have an influence and a potential role to play in fertilisation strategies for wheat. If modern wheat cultivars are shown to have an increased need for late-applied N, there is a question as to whether it would be best to apply this to leaves or soil?

In the light of the potential advantages of using foliar N, the aim of this review is to provide a succinct appraisal of the factors influencing the effectiveness of foliar N, crop performance, N recovery by the crop and the occurrence of crop damage. Relevant research is reviewed with the objective of indicating where future research and development should be focused to meet the needs of the industry now and into the foreseeable future, in particular the potential for foliar N to improve N use efficiency as a means of reducing

N losses to the environment.

The review builds on an earlier published review (Gooding and Davies, 1992), revisiting and re-interpreting findings in the light of new developments and technologies. The review comprises a number of technical sections. Summary conclusions are provided for growers to help optimise foliar N use, based on best available current knowledge. Identified topics requiring further research and development are detailed and prioritised.

2.0. Effects of foliar-applied nitrogen on grain protein and yield.

In commercial practice, foliar-applied nitrogen is applied as urea, which is available as a commercial nutrient spray solution containing up to 20 kg N per 100 litres of solution. This is close to the saturation point for urea, which limits the amount of nitrogen that can be applied in practice in a single application to about 60 kg ha^{-1} in 300 litres/ha. Solutions with higher N concentrations can be achieved by mixing urea and ammonium nitrate, but such solutions are unsuitable for foliar use due to high levels of leaf scorch from the nitrate component. Therefore, foliar urea is at best only likely to be used to substitute for a proportion of the total nitrogen requirement, or applied strategically where it provides additional benefits, i.e. for grain protein content.

Most research studies have tested foliar N as either a replacement for part of the spring-applied N, in some cases displacing the application timing to a period later in the growing season, or as an additional treatment in an attempt to boost grain protein levels. In the former cases the aim has been to reduce problems associated with nitrogen loss or availability, in the hope of increasing grain yields and/or grain protein levels.

2.1. Effects on wheat yield

Where extra nitrogen has been applied to wheat to boost grain protein levels (i.e. relatively late in the growing season) effects on yields have been variable, with contrasting effects recorded between seasons (Gooding *et al.*, 1987), or between sites (Dampney and Salmon, 1990, Sylvester-Bradley *et al.*, 1984). Foliar N application can increase yield on sites where nitrogen applied for yield has been sub-optimal (Sylvester-Bradley *et al.*, 1984). In some cases, yields following foliar N application have been lower than those following soil applied N, due at least in part, to effects of leaf scorch (Dampney and Salmon, 1990, Sylvester-Bradley *et al.*, 1984) (see section 4.0). In studies where foliar N was observed to have no effect on grain yield, this may have arisen as a result of applying foliar N too late to have any effect on leaf expansion or survival, and therefore any effect on the rate or duration of photosynthesis during grain filling (this topic is discussed in more detail in section 5.0).

Dampney and Salmon (1990) reported that in 2 out of 12 cases, there was a significant yield response to foliar N (40 kg ha^{-1}) applied between flag leaf emergence (GS 39)[2] and caryopsis hard (GS 90), though the magnitude of the yield response depended on the application timing (see below). A likely explanation for these yield responses is that the base nitrogen application rates were sub-optimal for yield. Out of 32 trials, Sylvester-Bradley *et al.* (1984) recorded significant yield responses ranging from 0.17 to 0.36 t ha^{-1} in only 4 cases when foliar N was applied during anthesis (GS 65), and in one case where foliar N was applied at medium milk (GS 75) (no details were presented on the size of the yield response achieved in this case).

Timing of foliar N application has an impact on yield. Dampney and Salmon (1990), found that in situations where there was a significant response to foliar N, applications made between boots swollen (GS 43) and ear ¾ emerged (GS 57) had the greatest effect and increased yield by between 1.02 and 1.08 t ha^{-1}. Applications made between the end of anthesis (GS 69) and early dough development (GS 83) increased yield by between 0.36 and 0.48 t ha^{-1}. Applications after soft dough (GS 85) had no effect on yield. Looking at a wider range of data sets, Dampney *et al.* (1995) found that mean yield response to foliar N was optimised by applications during ear emergence (+0.14 t ha^{-1}), followed by applications during anthesis (+0.08 t ha^{-1}), or grain milk development (+0.09 t ha^{-1}). Effects of foliar urea on grain yield may be more pronounced in dry years where uptake of soil applied N may be restricted, or in situations where rooting, or root efficiency is restricted e.g. where take-all disease is a problem.

Foliar N applied between flag leaf and ear emergence has been shown to increase grain number per ear and weight per grain (Lawlor *et al.*, 1989, Sadaphal and Das, 1966). Applications at and after anthesis have increased weight per grain (Smith *et al.*, 1987).

It seems clear that foliar N applied late in the season can increase yield where basal N dressings are sub-optimal and where it is applied prior to dough development in grain (GS 85). The question remains as to whether later applications of foliar N can make up fully for previous sub-optimal nitrogen use. There are very few studies reported in the literature where nitrogen response curves have been generated for both foliar urea and soil-applied nitrogen at a number of application timings to differentiate between effects of nitrogen source, rate and timing. However, individual aspects have been studied. Penny *et al.* (1978 & 1983) tested the effect of applying sprays of a urea/ammonium nitrate liquid fertiliser mix (supplying 50 kg ha^{-1} N, half applied at ear emergence followed by the remainder at anthesis) to winter wheat, which had been fertilised previously with 'Nitro-Chalk' (ammonium nitrate/calcium carbonate (25% N)) at rates ranging from nil to 150 kg ha^{-1} N. In this case, considering foliar urea as part of the total N dressing, in most cases foliar N was unable to make up for deficiencies in N applied earlier in the season (Figure 2). However, at application rates of 150 kg ha^{-1} N (which at the time was considered to be optimal for yield) yields were similar or higher where part of the dressing was applied as foliar N. (Published data in these studies which included the hot dry year of 1976, were omitted as part of the foliar N treatment was applied when the crop was already senescing). This work was done on the cultivars Capelle-Desprez (1974-75) and Maris

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[2] For a description of the cereal decimal growth stage see Tottman (1987).

Huntsman (1978-79), now outclassed by modern cultivars with significantly higher yield potential.

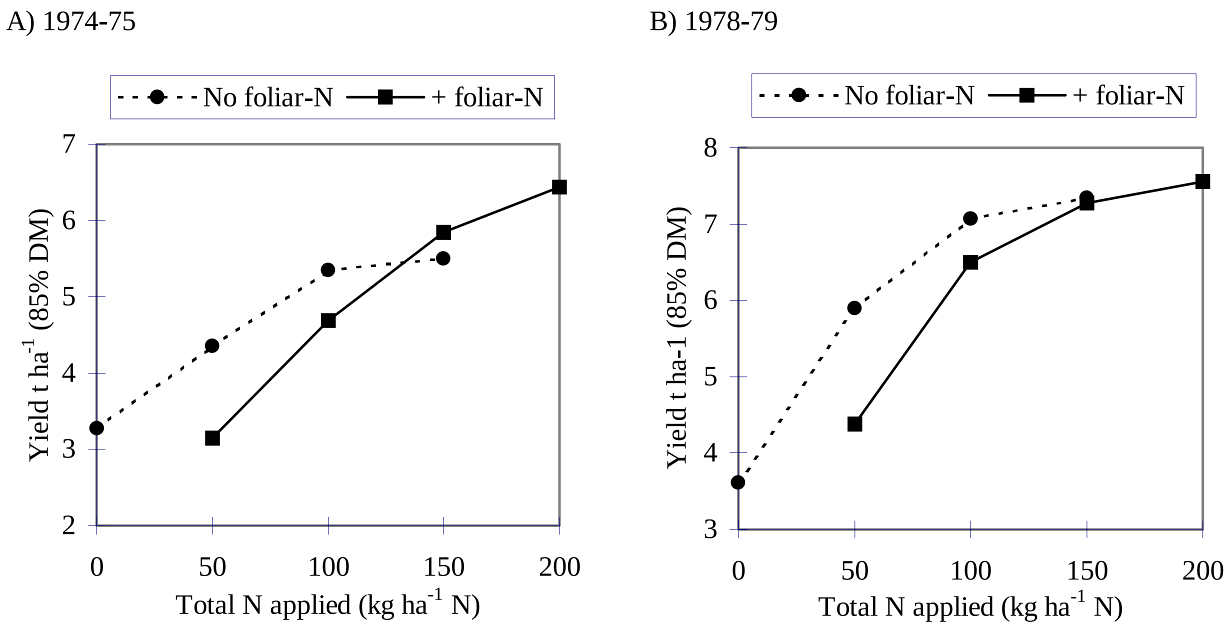

Figure 2. Effect of applying part (50 kg ha^{-1} N) of the wheat N dressing as foliar N on final yield. A) Mean data for 1974 and 1975 (Penny *et al*., 1978). B) Mean data for 1978 and 1979 (Penny *et al*., 1983).

Poulton *et al*. (1990) compared the effects of applying a spring soil-applied N solution (urea plus ammonium nitrate) with that of a four spray urea treatment applied between GS 32 and GS 51, designed to deliver the same total amount of nitrogen. Where the four spray programme was used, yields were reduced by 0.69 t ha^{-1} (9%). However, though N recoveries were lower for the four spray programme, the main cause of the yield depression was scorch damage, which occurred with the last two applications.

In 22 trials in the UK, Dampney *et al.* (1995), evaluated the effect on yield of applying a range of ‘top-up’ nitrogen rates ranging from 0 to 180 kg ha^{-1} N as either ammonium nitrate, applied in the spring (GS 32), or as foliar urea at GS 75. The base N-application rate for each site was judged to produce around 12.2% protein. Averaged over all sites, applying an extra 30 kg ha^{-1} N as ammonium nitrate increased yields by an average of 0.16 t ha^{-1}, foliar N increased yields by an average of 0.1 t ha^{-1}. At rates above 30 kg ha^{-1} N, foliar N was less efficient than where the same amount of N was applied in the spring and was not able to achieve the same maximum yield. Within this data set there were 9 sites where there was a significant yield response to additional nitrogen. In 4 of these cases foliar N gave a similar yield response to ammonium nitrate and in one case foliar N gave a higher yield response than ammonium nitrate. Leaf scorch was observed where foliar N was applied, but was not severe in the majority of cases (< 10% leaf scorch). Foliar N was beneficial where lodging was a problem.

Care has to be taken when interpreting foliar N studies to determine whether the foliar N is being applied in addition to a basal amount of nitrogen applied for optimum economic yield, and whether the basal nitrogen rate applied was optimal. Yield responses are only likely to be observed consistently where basal soil-applied nitrogen applications prove sub-optimal, and in situations where foliar N is applied earlier in the season than the optimum time for boosting grain protein content (see section 2.2.). The main way in which foliar N is likely to affect yield is through effects on canopy retention (section 5.0).

2.2. Effects on grain protein

To achieve a full premium, grain protein must usually reach 13% (100% DM). In general, the greater the grain protein concentration the greater the loaf volume (e.g. Finney *et al*., 1957). Foliar-applied nitrogen has generally proved to be more effective than granular N application in boosting grain protein, though not in all cases (e.g. Powlson *et al*., 1989). To boost grain protein, the optimum timing for foliar N has typically been shown to be during the period of anthesis (GS 60-69) (Gooding and Davies, 1992) or grain milk development (GS 70 to GS 79) (Clare *et al.,* 1993, Dampney, 1987, Dampney and Salmon, 1990, Dampney *et al.,* 1995, Smith *et al.,* 1987). If growth is curtailed, for example by summer drought then earlier applications of foliar N tend to optimise grain protein (Clare *et al.,* 1993). Foliar N applications after the late milky-ripe stage (GS 79), do not appear to be taken up and assimilated into grain protein. Yield responses are not likely at these later timings (section 2.1), as the capacity for carbohydrate accumulation is diminishing.

Foliar urea (50 kg/ha-N) applied at grain milky-ripe (GS 75) has been shown to increase grain protein content (100 % DM) by an average of 0.8 % (Dampney, 1987, Dampney *et al.,* 1985), and in some cases by up to 0.95 % by Rule (1987). However, the size of the response depends on the starting grain protein concentration. Dampney *et al.* (1985) found that the largest grain protein response (+0.84 %) to foliar N application was observed where control grain protein was low (< 12.4 %), and the lowest response (+0.2 %) was observed where grain protein was high (> 14.2 %) in the absence of foliar urea application. Grain protein content shows an almost linear response to additional foliar urea-N application rates (at GS 75) of up to 100 kg ha^{-1} N, at both low (< 12.2 %) and high (> 13.9 %) base levels of grain protein (Dampney *et al*., 1995). In practical situations applications are usually limited to around 40 kg/ha because of the risk of scorch damage, though application rates of up to 60 kg ha^{-1} N are being used successfully in commercial practice.

As with effects on yield noted above, soil nitrogen supply also influences the grain protein response to foliar N application. Foliar N applications are less effective in boosting grain protein where large amounts of N have previously been applied (Penny *et al*., 1983, Powlson *et al*., 1987).

In a series of 23 trials, Dampney *et al.* (1995) concluded that in most cases, use of ammonium nitrate alone as a N fertiliser, was unable to achieve the grain protein levels achieved by foliar N applications. Dampney *et al.* (1995) extrapolating from experimental data estimated that the grain protein content (100 % DM) could be boosted up to 16.6 % with large application rates of foliar urea (120 kg/ha or more), but only up to 14.8 % with similar rates of ammonium nitrate. Grain protein contents were increased by an average of 0.78 % by application of 30 kg ha^{-1} N as foliar urea at GS 75, and 0.60 % by application of the same amount of nitrogen as ammonium nitrate at GS 32. The rate of grain protein response to applied N was always greater for foliar urea.

Increases in grain protein content achieved by additional nitrogen fertiliser are relatively small. Dampney *et al.* (1995) estimated that use of extra nitrogen only resulted in achievement of a milling premium, which would otherwise have been unobtainable, in 25% of cases. In the remaining cases, the increase in grain protein would be insufficient to attain a premium, or protein levels would already have already been above the threshold. The difficulty lies in predicting final grain protein content at harvest so that fertiliser strategies can be optimised. Recently completed work, funded by the HGCA, has looked at the potential for grain protein prediction. Bhandari (2000), evaluated the use of Near Infrared Reflectance (NIR) techniques on immature grain at GS 75 and found that there was a good ($R^2 = 0.88$) straight-line relationship between NIR spectral data at this stage and final grain protein content at harvest. However, the technique still requires further validation to produce a wider range of data sets for evaluation, but if the method proves to be reliable, then this would be an important step forward in helping to optimise foliar N use to boost protein content.

Dampney *et al*. (1995) reported that increasing the amounts of nitrogen applied to soil or as foliar urea in an attempt to boost grain protein resulted in the extra nitrogen applied being used increasingly less efficiently by the crop. The apparent recovery in grain from 30 kg ha^{-1} extra N was only 30-35% (i.e. 20 kg ha^{-1} residue left in chaff, straw and soil), reducing to 20-25% at application rates of 120 kg ha^{-1} extra N (i.e. 90 kg ha^{-1} residue left). However, at 6 of 22 sites recovery of N in grain was significantly better where extra N was applied as foliar urea at GS75 than as granular ammonium nitrate at GS32. Similar effects were noted by Poulton *et al*. (1990). However, while recovery of N in grain can be improved by foliar urea applications, total recovery of the additional N applied can be lower than where all N is applied to soil earlier in the season (section 3.3).

2.3. Effects on bread-making quality

High protein content is indicative of a good extensible gluten level in the grain, essential for good bread-making dough. Gluten consists mainly of two types of storage protein, gliadin (soluble in alcohol) and glutenin (soluble in alkali). Other N-containing grain components include albumin and globulin proteins and free amino acids. There is no evidence that late application of foliar urea increases the very small non-protein N content of grain (Dampney *et al*., 1995).

Protein is not evenly distributed through the grain; concentration increases from the centre outwards, and not all grain protein is useful in bread-making. Protein associated with the aleurone layer and outermost layers of the grain and the wheat germ has no function in bread-making (Kent, 1982). In mature grain, 20% of the grain protein content is contained in the wheat germ.

For bread-making wheat, within the normal grain protein range, there should be a positive correlation between grain protein content and loaf quality (Finney *et al*., 1957). However, an improvement in grain protein content does not always manifest itself in an increase in bread-making quality; even where other milling quality parameters (e.g. Hagberg Falling Number tests) are met (Rule, 1987, Sylvester-Bradley, 1990). This is not due to effects of retention of nitrogen on the grain surface following foliar application, as the enclosed grain in its floret is protected from urea deposition by the lemma and palea of each floret (Sylvester-Bradley *et al*., 1987).

Foliar N applications have been demonstrated to improve bread-making quality in some studies. Dampney *et al.* (1995) showed that foliar urea induced extra protein in grain by increasing the gliadin content. It was hypothesised that spring-applied ammonium nitrate channelled nitrogen more strongly into albumin and globulin proteins because of its earlier availability when protein synthesis starts in the seed embryo. Foliar urea application during grain development may tend to be channelled into gluten proteins, whose synthesis would be maximal at the later time of application. Evidence for this hypothesis was only supported at the extremes of treatment by analysis of individual grain proteins. However, functional tests of grain protein strength (measured by elastic modulus (G’)) suggested that foliar urea applications increased the high quality glutenin component.

Effects of foliar urea on components of grain protein and bread-making quality have been reviewed elsewhere (Gooding and Davies, 1992), and indicate that there is variability in effects on the balance of grain protein components. Grain protein constituents are probably influenced by factors such as nutrient status, plant health and growing conditions, and differences in methods of analysis may also affect results. However, the extra protein derived from foliar urea in general appears to be as effective in increasing loaf volume as soil-applied nitrogen.

These studies do indicate that moving from soil-applied to later foliar-applied nitrogen fertilisation could affect the proportion and/or composition of grain storage proteins in harvested grain. The implications of this are likely to be of relatively minor significance for most applications. However, if there is a shift within the industry towards premium payments based on grain protein quality, as opposed to grain N content alone, this may affect growers strategies and may increase interest in foliar-urea applications.

As breeders increase grain yields of bread-making wheat, and annual sulphur deposition decreases, one of the factors that may need attention is sulphur fertilisation to maintain N:S ratio in grain. Where this ratio increases, grain protein quality is affected, with low quality (sulphur deficient) omega-gliadin content increasing, and the more desirable high molecular weight glutenin content decreasing (Timms *et al*., 1981). Attention to sulphur status of crops may be required to ensure grain protein quality is not compromised.

3.0. Factors affecting uptake and efficiency of crop recovery of foliar N

A number of factors influence crop uptake of foliar N, including crop interception of sprays, spray deposition pattern and spray retention, urease hydrolysis at the leaf surface, rates of ammonia volatilisation after hydrolysis in the leaf, leaf cuticle characteristics and speed of absorption, and assimilation. Inefficiencies may occur at each stage.

3.1. Spray deposition

The deposition distribution pattern of foliar sprays in the wheat crop canopy depends on the rate at which spray droplets are intercepted by the crop. The deeper the penetration into a crop canopy the greater the reduction in interception (Göhlich, 1985). Generally small droplets, less than 100 µm in diameter, optimise spray retention by cereals. However this equates to a very fine spray which would increase losses associated with wind drift. Larger droplets will settle on the upper part of the canopy and result in less penetration. For foliar urea sprays this would be a benefit by reducing losses to soil. However, Taylor and Anderson (1987), examining spray volumes ranging from 100 to 300 l/ha, at three spray qualities (fine, medium and coarse), found that growth stage of the crop had the greatest effect on spray deposition, and spray quality and spray volume had very little consistent effect on deposition rates or penetration into the crop canopy.

Green area index (GAI) also affects spray penetration and interception rates. In cotton crops, Bache (1985), estimated that in a dense canopy (GAI 6), 57% of a spray would be intercepted in the top 40 cm of the crop canopy, but 67% would be intercepted in a less dense crop (GAI 4). Grayson and McCarthy (1987), found that typically at full ear emergence, 12% of an applied spray was intercepted by the ear, 65% by the flag leaf and 22.5% by leaf 2. In studies with foliar urea, Hopkinson (1998) found that a wheat canopy intercepted approximately 60% of a foliar urea spray, and that 12% was deposited on ears, 30% on the flag leaf and 12 % on leaf 2. In this study, approximately 25% of the applied spray reached the soil surface.

The N loss pathways associated with application of foliar N sprays can be summarised as a proportion of the total application leaving the spray boom (Table 1).

Spray deposition will also depend on leaf orientation and shading effects etc. More vertically orientated leaves also tend to have more spray deposited on leaf tip sections than those that have a more horizontal habit (Koch and Spieles, 1992), though the total deposition is lower on vertically orientated leaves.

Table 1. N losses associated with foliar urea application to wheat crops (after Hopkinson, 1998)

N not deposited on the crop immediately after spraying	35%
N lost from crop surface within minutes of application	10%
N lost from crop surface over 4 days	10%
Uptake by crop	30%
Remaining on crop surface after 4 days	15%

Sylvester-Bradley, Rochford and Rule (1990), investigated the effects of parting the crop canopy to increase urea spray deposition within the crop canopy, by using the ‘crop tilter’ system, whereby a bar in front of the spray boom parts the crop and angled nozzles spray down into the parted crop canopy. Canopy disturbance had no consistent effect on grain nitrogen content, but did increase nitrogen uptake by a small amount in some cases. However crop disturbance alone increased yield for reasons that were not clear, and it was concluded that further work was required.

Adjuvants are used conventionally to improve agrochemical spray retention, penetration of active ingredients and to increase spray coverage of leaves. With respect to urea there are three categories of potential interest:

Penetrants	to aid penetration of cuticle waxes.
Wetters/Spreaders	to reduce the surface tension of spray droplets thereby increasing spread over the leaf surface.
Stickers	Gums, resins or solvents, which help droplets stick to leaves

When considering the effects of such products on urea uptake, is should be noted that detrimental effects could also arise. Applying urea with wetters has been seen to increase levels of leaf scorch (see section 4.0) (Poulton *et al.*, 1990, Powlson *et al.*, 1989). Hopkinson (1998), evaluated the effects of a spreader, a penetrant and sticker on crop retention of foliar urea under controlled conditions (Table 2).

The penetrant LI700 and the wetter Silwett L-77 resulted in urea rapidly being ‘lost’ from the leaf surface. It is assumed that this equates to absorption of urea by leaves, but this is not entirely clear as in related field studies LI700 and Silwett L-77 reduced the proportion of applied urea retained by the crop at the time of application. No effects of adjuvants on leaf scorch were reported in this work. The roles of adjuvants in helping to manage foliar nutrition of wheat needs further detailed study.

Table 2. Effects of adjuvants (applied as a 0.1% solution with foliar-applied aqueous urea) on speed of removal of urea (15 kg N ha^{-1}) from the surface of cereal flag leaves (determined by leaf washing technique (plants grown under glasshouse conditions)) (Hopkinson, 1998).

Adjuvant	Type		Urea half life (hours)
No adjuvant			48.6
Silwet L-77	Spreader	(Organosilicone surfactant)	1.4
LI700	Penetrant	(Soya lecithin based)	1.5
Spray Fix	Sticker	(Latex based)	44.4

3.2. Volatilisation losses of N applied as urea

Breakdown by hydrolysis of urea to ammonia and carbon dioxide is facilitated by urease enzyme activity in leaf tissues and phylloplane (leaf-surface dwelling) bacteria. Hydrolysis is essential for assimilation of urea-N by the crop, but it is also a significant source of N loss via volatilisation of ammonia from leaves and leaf surfaces. In UK conditions it has been estimated that around 10% of the urea-N applied to wheat may be lost by volatilisation (Hopkinson 1998). However in other studies up to 50% of the applied N has been lost by such means (Bremner, 1990). On turf-grasses, losses of up to 35% have been recorded, attributed to volatilisation of ammonia within 24 hours of application (Bowman *et al*., 1987). Higher losses are only prevented by the rapid uptake of urea into the crop. In contrast to foliar N, only 0.8 % of the N applied as ammonium nitrate is subject to ammonia volatilisation (Harrison and Webb, 2001). The volatilisation losses estimated for foliar-applied urea-N, are very similar to those derived for solid or liquid solutions of urea applied directly to soil (11.5%) (Harrison and Webb, 2001).

Urease inhibitors (phosphoroamide compounds – see Bremner, 1990) broadcast with solid urea to soil have reduced the amount of N lost by volatilisation (Rogers *et al.*, 1987). However, when used with foliar urea, there are potential problems. Working with soybean, Krogmeier *et al.* (1989) found that applying the urease inhibitor PPD (phenyl-phosphorodamidate) with foliar urea increased the urea content, and decreased the ammonia content and urease activity of leaves. However, it also increased leaf tip necrosis, which was attributed to the accumulation of urea to toxic levels. Powlson *et al.* (1989) also found that adding the urease inhibitor PPD to urea solutions caused scorch on wheat. The topic of leaf scorch is discussed in more detail in section 4.0.

Urea is taken up rapidly. Urea and ammonia content of barley leaves can be significantly increased within four hours of urea application. Turley and Ching (1986) found that urea content of leaves peaked within an hour of urea application, before declining to levels in untreated leaves. In ryegrass 40% of applied urea is absorbed between 12 and 24 hours after application, and the process of hydrolysis is rapid within the leaf (Bowman and Paul, 1992). Uptake also tends to be greater in younger leaves (Klein and Winterbaum, 1985). The cuticle is the main barrier to urea uptake and urea penetrates this primarily by diffusion, following a concentration gradient. The speed of passage through the cuticle depends on cuticle thickness and the amount of wax present. As older leaves tend to have greater deposits of wax, this may explain part of the difference in uptake between young and older leaves. Uptake of urea may be mediated to some extent by leaf cuticle morphology.

N taken up by the crop can be rapidly mobilised within the plant. It has been hypothesised that N derived from foliar urea enters more readily mobilised pools of nitrogen in the plant than those derived from soil-applied nitrogen. This is based on work in maize which demonstrated that urea-N taken up in leaves was readily transported to grain from pre and post-anthesis applications, and not stored in stem reserves (Below *et al*., 1985). Hopkinson (1998) also demonstrated that within 96 hours, labelled nitrogen applied to the flag leaf was rapidly transported to the rest of the plant.

Work has started to look at whether controlling the rate of urease activity in plants could minimise NH_3 losses. Work at the Scottish Crop Research Institute with potato crops has started to provide detailed knowledge of the urease enzyme and factors affecting its activation (Witte *et al*., 2001). The effect of differing levels of urease activity in transgenic potato plants on NH_3 losses has been studied (Claus-Peter Witte personal communication). In transgenic plants, reduced urease activity to 30% of that of control crops resulted in higher concentrations of urea and lower concentrations of ammonium accumulating in leaves as a result of slower urea degradation. In the control crops, ammonium concentrations were 4-5 times higher than those in transgenic plants. However, volatilisation losses, which ranged from 10 to 18% were unaffected by leaf ammonium concentration, and there was no significant difference in recoveries of labelled urea-N. Similar results were obtained using transgenic potato lines where in contrast urease activity was increased (> 2 fold) compared to control plants. It was concluded that reduction in urease activity did not affect NH_3 volatilisation losses in the situations tested, but that more work was required to examine effects on nitrogen use efficiencies. The rate of urease activity in wheat has been shown to be 52 % higher that in potato crops (Witte and Medina-Escobar, 2001). In contrast to effects in potato crops, in transgenic barley crops, where the activity of glutamine synthetase (which mediates the conversion of ammonium to amides) has been reduced by 47-66%, after urea application, the ammonium content of barley leaves increased and ammonia emissions increased in relation to leaf ammonium concentration (Mattsson *et al*., 1997). Work has started at Rothamsted to enhance the activity of glutamine synthetase in leaves. If ammonia losses in wheat are more sensitively related to leaf ammonium concentration than initial results from potato crops suggest, then manipulation of glutamine synthetase activity could be a means of significantly reducing the problem of ammonia volatilisation, and could also have implications on levels of leaf scorch damage and on N utilisation.

3.3. Crop recovery of foliar N

In order to minimise the quantity of residual N left after harvest which will be susceptible to leaching and pollution of waters with nitrates, crop recovery of all sources of applied N needs to be maximised. Sylvester-Bradley and George (1987) concluded that the extra granular N applied to boost grain protein could have implications on nitrogen leakage from the crop-soil system, as typically only 22% of the N applied was recovered in grain. In studies using labelled (N^{15}) urea applied to wheat crops (at 40 kg ha^{-1} N), recovery of N in the crop at harvest was optimised at 65-70% by applications during anthesis. Of the N recovered in the crop, 90-94% was present in grain (Powlson *et al*., 1989). Similar recoveries have been reported in other studies (Powlson *et al*. 1987, Smith *et al*. 1991 and Hopkinson, 1998). Recoveries of N in grain have been shown to be greater from foliar N applied late in the season than from fertiliser applied to the soil earlier in the season (Dampney *et al.*, 1995, Poulton *et al.*, 1990, Powlson *et al*., 1987 & 1989). Reported recoveries of foliar N in grain range from 30-35% (Dampney *et al.* 1995) up to 64% (Powlson *et al*. 1989) for applications made between anthesis and grain milky ripe. Where labelled foliar N was applied at flag leaf emergence recoveries were similar (64% (Powlson *et al*., 1989)) or lower (49% (Poulton *et al*., 1990)) than where nitrogen was soil applied, but, 82-88% of the applied N was still recovered in the grain. Between 2% and 8% of applied foliar-N was found to be present in soil (0-5 cm) at harvest for applications made between GS 37 and GS 51 (Poulton *et al*., 1990).

Overall losses of nitrogen from the soil and crop system associated with foliar-application of urea may be greater than those associated with soil-applied nitrogen. Poulton *et al*. (1990) recorded unaccountable ‘losses’ from the crop and soil amounting to 23% where nitrogen was soil-applied, attributable to denitrification and leaching loss, but ‘losses’ increased to 30-40% with foliar-applied urea-N.

The figures for crop recovery (i.e. excluding soil residues) of foliar applied urea-N are very similar to figures derived for soil applied nitrogen. On average only 60% of the N applied to soil is recovered by the crop (Bloom *et al*., 1988; Scott *et al.*, 1994). The loss processes affecting foliar N applications would seem to be fewer and more open to manipulation than the loss processes affecting soil-N applications. Hence it is expected that after further research and development, foliar-applied nitrogen would be better utilised than soil-applied nitrogen by missing out on the N loss processes involved in soil.

4.0. Leaf scorch

One of the major limitations with use of urea is the commonly encountered problem of leaf scorch; whereby leaf tips or margins, particularly of the flag leaf, become yellowed and necrotic. Scorch is a particular problem with application of high rates of urea or concentrated solutions and is of increasing concern where strobilurin fungicides are used where the beneficial effects achieved in the absence of disease have been attributed to extending green leaf area duration (see section 5.1). Leaf scorch levels of between 30 and 40% of flag leaf area were reported with high (multiple) application rates of foliar N (up to 180 kg/ha N), which resulted in yield depressions of between 0.24 and 0.5 t/ha (Dampney and Salmon, 1990; Sylvester-Bradley *et al*., 1984).

Dampney and Salmon (1990) found that foliar-urea application rates above 30 kg/ha N caused scorch, but at only 1 out of 9 sites did this exceed 10% of flag leaf area scorched. Sylvester-Bradley *et al.* (1984) recorded an average leaf scorch of 10 % of flag leaf area over 14 trial sites for a range of foliar urea application rates up to 60 kg ha^{-1} urea-N. For the lowest rates of application tested (20 or 40 kg/ha N) the worst level of leaf scorch recorded was 20% leaf damage.

Leaf scorch tends to be exacerbated where foliar urea is applied earlier in the season and where conditions are warm, sunny and windy (Peltonen, 1993). However, Sylvester-Bradley *et al.* (1984) found no evidence that leaf scorch was worse in hot dry years. In greenhouse studies with wheat, Peltonen *et al.* (1991) found that leaf scorch depended on the leaf being wet for an extended period of time. This is supported in field conditions where scorch has been severe when urea is applied early in the morning when dew is still present on the crop (Gooding 1988, cited by Gooding and Davies, 1992).

Scorch has been attributed to the direct desiccation of cells by urea solutions drying out and concentrating on the leaf. This is said to remove water from the leaf by osmosis (Syverud *et al*., 1980, Gamble and Emino, 1987). It can be hypothesised that this would produce a spotting pattern on the leaf, whereas scorch of the leaf tip and edge is the most common observation. Urea has a low salt index (Grey, 1977) which should reduce the effects of direct osmotic damage to leaves. However direct damage to cells on crops such as maize has been observed (Gamble and Emino, 1987). The low salt index of urea means that the risk of scorch is less with urea than other forms of N fertiliser such as ammonium nitrate or ammonium sulphate.

Leaf-tip scorch is usually attributed to accumulation of ammonium in the leaf after *in-vivo* hydrolysis of urea. This increases the leaf pH, and may have other effects on leaf metabolism or respiration. The ammonium produced by hydrolysis is assimilated into amides through glutamine synthesis, then into amino acids, proteins and other nitrogenous leaf constituents.

Krogmeier *et al.* (1989), applying urea with urease inhibitors, concluded that leaf tip necrosis in soybean arose not from the accumulation of ammonia, but from urea, as necrotic tissue contained more urea then unaffected areas of leaf. Foy *et al.* (1953) working with maize, also found no evidence that accumulation of ammonia in leaves was associated with scorch severity. Highest levels of scorch were associated with elevated levels of urea in the leaves, but it was concluded that direct injury to leaf tissues was unlikely, and effects on metabolism was a more likely explanation.

Care has to be taken in the interpretation of some work prior to 1970's, as urea fertilisers produced during this period were potentially contaminated with the toxic by-product 'biuret'. However, reviewing this topic, Gooding and Davies (1992), reported that visual symptoms of damage had not been seen at high concentrations of biuret, though reductions in yield could still occur.

Foy *et al*. (1953), cited the findings of several American studies which showed that addition of sucrose, potassium bicarbonate or calcium hydroxide to urea sprays reduced scorch damage in crops. Hinsvark *et al*. (1953), measured the evolution of C^{14}-labelled CO_2 resulting from hydrolysis of labelled urea applied to vegetable crops, and it was found that addition of sucrose significantly reduced the rate of urea hydrolysis. Working with maize, Foy *et al.* (1953) found that addition of potassium bicarbonate increased levels of damage, while addition of sucrose reduced damage from severe to moderate levels. Addition of sucrose with urea resulted in elevated levels of reducing sugar in the leaf. It was hypothesised that accumulation of products from metabolism of ammonia in the leaf, such as amino acids or polypeptides may be responsible for leaf damage, where the rate of protein synthesis lags behind, or is blocked. In some cases, the activity of urease may not be matched by that of glutamine synthetase, leading to accumulations of ammonium to toxic levels. This may be exacerbated in dry conditions.

Foy *et al.* (1953) presented supporting evidence that sucrose reduced absorption rates of urea, and it was hypothesised that sucrose may also increase the translocation of urea, or its products, in the leaf. The latter hypothesis is supported by Weintraub and Brown (1950); cited by Foy *et al*. (1953), which demonstrated that translocation of herbicides in plants (including a urea compound) was increased by addition of sucrose.

Applying urea with wetters has also increased scorch damage as described earlier (section 3.1) and applying urea in mixture with fungicides containing wetters can pose an increased risk of scorch (Gooding, 1988). Effects of wetters are probably attributable to their effects on the rate of urea penetration of the leaf (section 3.1).

Grey (1977) suggested that small droplet sizes could increase leaf coverage, and hence reduce the risk of leaf scorch, and this has been shown in maize (Chesnin and Shafer, 1953). Scorch can also be reduced by splitting the dose between applications a few days apart, and by increasing the dilution of urea.

Some commercial formulations of urea are also marketed which are purported to reduce leaf scorch. 'Sunburst' is marketed as a urea-N solution with contains calcium oxide and calcium chloride. It is a foliar N product which is reported to reduce the risk of scorch and increase the efficiency of use compared to conventional urea-N sprays. Foy *et al*. (1953) found that addition of calcium hydroxide to urea sprays reduced scorch damage.

Limited work to date suggests that cultivar can have an influence on the expression of scorch (Gooding, 1988, cited by Gooding and Davies, 1992)). Differences in leaf morphology and physiology may play a role in such cases and this warrants further study.

Work has started at Rothamsted to manipulate wheat to enhance the activity of glutamine synthetase in leaves. If the imbalance between rates of urease and glutamine synthetase activity is a major cause of scorch in wheat, due to accumulation of ammonium, then this could be a means of significantly reducing or eradicating the problem. If and when such traits are successfully incorporated into commercial wheat cultivars, work will be required to evaluate their effectiveness.

5.0. Retention of green leaf area

Once grain-fill commences, 20-50% of the final grain weight is sourced from the re-mobilisation of reserves stored in the green canopy (i.e. fructose in the stem and proteins in the leaves). Photosynthesis by the flag leaf, and to a lesser extent by leaves two and three, supplies the remainder of the grain weight. The persistence of the canopy, particularly the flag leaf is therefore critical in determining grain yield (HGCA Wheat Growth Guide, 1997). Nitrogen in the canopy is also re-mobilised; up to 75% of nitrogen taken up by the crop is used to form grain proteins (Sylvester-Bradley and Scott, 1990). Gregory, Marshall and Biscoe (1981) showed that, as N was re-mobilised from leaves, there was a corresponding reduction in the rate of photosynthesis; suggesting that continued grain growth depends on the presence of sufficient nitrogen in the canopy to maintain the rate of photosynthesis and delay the onset of senescence.

Foliar urea applied just prior to ear emergence has been shown to delay leaf senescence, prolonging photosynthesis and green leaf area (Lawlor *et al*., 1987) for about a week, and in some extreme cases by up to 20 days (Harms and Nowak, 1990). As the grain 'sink' for nitrogen increases, and nitrogen is remobilised from the canopy and directed towards grain production, there may be advantages in early foliar N applications (i.e. prior to anthesis), to boost the canopy nitrogen content and extend the life of the crop canopy. In a review of the limited studies available, Gooding and Davies (1992) indicated that application of foliar N increased leaf nitrogen content in wheat (and related cereal species) up until grain maturity, though in other studies, applications around anthesis had no effect on leaf nitrogen content during grain filling. Factors such as soil nitrogen supply will affect the results of such studies. At fertiliser N rates close to the optimum, applications of foliar N are most likely to have little or no effect on leaf N content, compared to effects at sub-optimal or nil rates of spring-applied nitrogen (Lawlor *et al*., 1989). Increasing the duration of the canopy has been estimated to be worth around 0.2 t ha^{-1} yield per day during the critical grain-filling period.

5.1. Foliar N and strobilurin fungicides

Strobilurin fungicides were introduced to the UK in 1997, and it was soon noted that these fungicides appeared to have physiological effects on crops such as longer retention of green leaf area, increased chlorophyll content and greater light absorption (Jones and Bryson, 1998). Previous and current HGCA-funded work in-progress has demonstrated that strobilurin-based fungicide programmes can provide an additional yield benefit of between 0.5 and 1.0 t/ha over triazole-based fungicides, irrespective of effects on disease control (HGCA, 2000). Limited work (B. Clark personal communication) has shown that optimum nitrogen rates are no different for strobilurin treated crops even where yields have increased by around 1 t/ha, but grain proteins can be significantly lower. Further work is required in this area. Foliar N applications are recommended where milling premiums are sought (HGCA, 2000). The targeting of such fungicides to GS 32 and GS 39 timings could increase pressure on nitrogen supply late in the season. There could therefore be additional benefits from use of foliar urea sprays with strobilurins, by prolonging green leaf retention, enhancing the strobilurin effect on yield and maintaining grain protein concentrations. Applying urea after flag leaf emergence could help retain green leaf area, and help boost yield. Later applications, at or around anthesis, could help maintain grain protein content in high yielding situations. However, any scorch damage induced by foliar N may be a greater problem in strobilurin-treated crops where green leaf area is retained for a longer period of time.

6.0. Discussion

Meeting the needs of high-yielding wheat crops

As demonstrated in the introduction, with increasing grain yields and little increase in fertiliser N use over the last 15 years years, UK wheat crops are starting to show a trend towards declining protein content. The situation is likely to get worse as costs of nitrogen increase. Ammonium nitrate is becoming a premium product on the world market, with volumes on the open market declining and prices increasing. In the meantime crop values remain low. This means that the economic breakeven ratio for cereals (as used to calculate the economic breakeven optimum fertiliser application rate) is widening, which has the effect of reducing the economic optimum nitrogen rate (MAFF, 2000). The DEFRA recommendations for fertilisation of arable and horticultural crops (MAFF, 2000) are based on these break-even calculations. In 2001, in response to increasing nitrogen cost, ADAS has recommended that the recommended economic optimum N rate for cereals should be reduced by 20 kg/ha N on average. Increasing nitrogen price will therefore exacerbate the current problem of declining grain protein content.

Further pressure on maintenance of grain protein will arise with the advent of a number of very high yielding milling quality varieties. High yield equates with high N demand unless improved nitrogen use efficiency by the crop can be demonstrated. In NIAB trials in 2000, the new cultivar Xi 19 with milling potential produced yields close to 11 t ha^{-1}.

Typically, benchmark crops yielding 9 t ha^{-1} take up around 244 kg ha^{-1} by harvest (HGCA Wheat Growth Guide, 1997). It will be very difficult to produce the large canopies needed to absorb and store close to the 300 kg ha^{-1} N required for an 11 tonne crop (which will be re-directed towards grain production in the reproductive growth phase) without incurring problems such as lodging, and pressures to stem nitrogen losses etc. In addition, dry soil conditions may restrict soil nitrogen uptake later in the season. So, there is a need to develop ways of getting nitrogen into crops while minimising lodging and N loss problems.

There could be additional benefits from use of foliar urea sprays where strobilurin fungicides are used on wheat, where it could help to prolong green leaf retention which is already enhanced by strobilurin fungicides, an effect which has been cited as accounting for the effect of strobilurin fungicides on yield of wheat in the absence of disease pressure (Jones and Bryson, 1998).

Meeting the nitrogen demands of both high yield and high grain protein, without increasing lodging risk, disease pressures and other problems associated with high nitrogen use, means that a greater proportion of the total nitrogen demand will most likely have to be met from applications later in the growing season. Foliar N could have a significant role to play in this situation. Optimum timings to boost yield and/or grain protein content are known, and there is no evidence that use of late-N affects the protein quality for baking uses. However, utilisation needs to be improved, losses minimised and risks of any scorch damage reduced to improve responses to applied N, and to encourage use by growers.

Does foliar N have a role in canopy management strategies?

The aim of canopy management strategies is to better target N use to crop demand by tactical applications of nitrogen. This inevitably means nitrogen is applied later in the season than would normally be the case with conventional fertiliser regimes based on soil-applied N, with the emphasis being on canopy survival during the grain filling stage rather than on canopy expansion during stem extension. Conventional fertiliser regimes promote a rapid rate of N uptake during stem extension, which then reverts to rates observed in unfertilised crops during the grain filling stage. In contrast where canopy management techniques are used, the same amount of applied N can be split between more applications and more N is applied later, even up to when the crop is flowering, without affecting final shoot N content (Sylvester-Bradley and Stokes, 2001). Late N applications have been shown to increase N uptake, even where June and July rainfall was only between 31 and 43% of the long-term average. However, previous HGCA work demonstrated that canopy management sometimes encountered problems in dry conditions on drought-prone soils (Stokes *et al.*, 1998). As a result, there is likely to be interest in the potential for use of foliar N to manage canopies late in the growing season. Using foliar N with canopy management techniques did help in achievement of grain protein targets, which were sometimes difficult to achieve with soil-applied N alone.

There remains a question whether late applications of foliar N can make up fully for previous sub-optimal nitrogen use. Though there is potential to use foliar-applied urea to make tactical applications of nitrogen to crops, there is not enough information available yet to make firm recommendations and further research and development is required in this area.

Clearly there is the potential for an increasing role for use of foliar-urea in wheat crops in the near future.

However there remain problems with N losses during application and uptake, and scorch damage under some circumstances. The efficiencies of crop recovery of late-applied foliar N and granular-N, applied earlier in the season, are variable but similar in magnitude. However the causes of inefficiency are different, and in the case of foliar urea should be amenable to technical improvement.

Improving the efficiency of urea-N use

Overall losses of nitrogen from the soil and crop system associated with foliar-application of urea may be greater than those associated with soil-applied nitrogen. Further work is required to identify and quantify the loss pathways associated with foliar N application.

There should be opportunities to increase the amount of foliar N which reaches and remains on the leaf surface. However the literature reviewed suggested that little could be gained from altering spray quality (volume or droplet size). Air-assisted spray systems may help increase crop coverage and reduce drift loses, but work is require to verify this. Crop phenotype may also have an influence on spray retention, as leaf angle and leaf size will affect how sprays are shed or retained by leaves and this perhaps warrants further investigation. Very limited work to date on spreader and penetrant adjuvants has shown that they can influence spray retention on leaves and uptake of urea, though more detailed study is required and implications of increased urea uptake on the risk of scorch damage needs to be evaluated.

The volatilisation losses of ammonia associated with foliar-applied urea-N are significant, accounting for around 10 % of the N applied. Volatilisation losses could theoretically be reduced by a number of means which could include increasing the rate of absorption into leaves, applying urea in mixture with urease inhibitors or by genetically altering plant metabolism by modifying the rate of activity of urease or glutamine synthetase. The latter perhaps would not receive public support in light of current views on genetically modified organisms unless such traits could be bred into commercial lines through traditional breeding methods. With regard to other mechanisms, adjuvants may have an effect and a role to play; though this needs to be fully evaluated. Urease inhibitors have reduced N losses associated with soil-applied N but foliar application presents more difficulties. There does appear to be scope for further evaluation in this area.

Scorch

Scorch is not a major problem where urea application rates are relatively low (40 kg ha^{-1} N) and precautions are taken to ensure urea is not applied in situations where there is a high plant transpiration rate (i.e. warm, sunny and/ or windy conditions). The causes of scorch are still not clearly understood but accumulation of urea or ammonium have been commonly cited as causes. Factors which reduce the rate of urea absorption may help reduce the incidence of scorch, though this could potentially increase losses due to volatilisation. Factors which may help mediate the rate of urea transport across the leaf surface include differences in leaf morphology, which have received little attention to date and warrant further study. The work started at

Rothamsted to enhance the activity of glutamine synthetase in leaves should provide a useful tool to examine the effect of the rate of N transformation processes in the leaf on the expression of scorch damage to help pinpoint the causes. If accumulation of ammonium is a major cause of scorch, then the ability to regulate the rate of glutamine synthetase activity could provide a means of significantly reducing or eradicating the problem. If and when such traits are successfully incorporated into commercial wheat cultivars, work will be required to evaluate their effectiveness.

Environmental impacts of volatilisation losses of NH_3

Environmental problems may arise when nitrogen is lost from the crop/soil environment as nitrate (NO_3), ammonia (NH_3) or nitrous oxide (N_2O). These losses are increasingly the subject of EU legislation and intergovernmental agreements. Requirements for reductions in NH_3 emissions are currently being debated by the UN Economic Commission for Europe (UNECE) which is drawing up protocols to reduce atmospheric pollution and acid deposition (Bull & Sutton, 1998). As atmospheric SO_2 levels continue to decline, NH_3 is cited as being responsible for acidification of rain, and it is also cited as a direct pollutant in protected nutrient-depleted habitats. However, the overall contribution of foliar urea to such problems in the UK is insignificant compared to the NH_3 losses emanating from UK livestock farming systems. For all fertiliser sources there is a need to consolidate studies of individual pollutants by examining N losses as a whole.

6.1. Key summary points for growers

Grain protein

- Applied at the right time, foliar urea-N is more effective in boosting grain nitrogen (protein) content than granular nitrogen. Typically, 30 kg ha^{-1} N will boost grain protein content by 0.8% when applied as foliar N and by 0.6% when applied as granular N.
- Application of foliar urea between anthesis and late milk development (GS 65 - 79) is most likely to have the largest effect on grain protein concentration.
- Grain protein will respond to increasing foliar N application rates up to c.100 kg/ha N, even in high fertility situations.
- The extra protein generated by late foliar N application is of a high quality and will not adversely affect bread-making qualities.
- There is a need to maintain Nitrogen:Sulphur ratios to ensure grain protein quality is not compromised.

Grain yield

- Yield responses to foliar urea are variable, and in general yield responses decline when application is delayed much beyond flag leaf emergence.
- Applications of foliar urea at flag leaf or ear emergence are most likely to boost green leaf area, leaf nitrogen content and prolong the duration of canopy green area and photosynthesis by a few to several days, which may increase yield. In total up to 35% of crop N demand (averaging 85 kg/ha N) is accumulated after the flag leaf has emerged (typically from mid-May onwards), when soil conditions can limit nitrogen uptake.

Efficiency of N recovery

- The efficiency of crop uptake of late foliar N is similar to that for soil-applied nitrogen (approximately 65-70% recovery).

Avoiding scorch

- Scorch is a potential problem particularly where concentrated (20%) urea solutions are used. Foliar N application rates of 30-40 kg/ha N can cause scorch, but typically only 10% or less of the flag leaf area is affected. Scorch of between 30% and 40% of the flag leaf area is possible from high (multiple) applications of foliar N, and yield depressions of up to 0.5 t/ha are possible at these high rates. Larger detrimental effects may be possible where strobilurin fungicides prolong green leaf area.

- The risk of scorch can be reduced by increasing dilution/reducing N concentration of the urea solution and avoiding application during hot, bright conditions. Splitting high application rates with a few days gap between applications may reduce scorch risk.
- Factors such as previous agrochemical treatments (with wetters etc) or rapid periods of growth may have an influence on the leaf cuticle and protective layers and may affect the rate of urea absorption by leaves. Where the rate of uptake is increased the risk of scorch is increased.
- Applying urea in mixture with fungicides that include wetters or other adjuvants is approved but the effect of tank mixing on scorch risk is not known. Care should be taken when selecting tank mix partners for urea sprays, the application of which may coincide with ‘ear wash’ fungicide sprays.
- Environmental factors which have been reported to increase the risk of scorch damage include applications under warm or windy conditions or where the leaf is wet for an extended period of time, i.e. when dew is still present on the crop. The best conditions for treatment are when the following 48 hours are forecast to be calm, cool and dull.

7.0 Further R&D requirements

1) Prediction of grain protein content.

Work is required to identify those crops, particularly up-and-coming high-yielding milling wheats, which need extra nitrogen in order to achieve grain protein targets, and the rate of application that would be required. A method is required to predict grain N content at or before GS75 so that the need for foliar N can be better targeted. Recent HGCA-funded work in this area (Bhandari, 2000), is an important development towards predicting final grain protein content and further work is required to prove and refine this new methodology. Success in this area would help reduce ineffective use of foliar N in milling wheat, given that previous work has indicated that extra N was only cost-effective in about 25% of fields treated. An effective prediction method would reduce costs to UK quality wheat growers and minimise any undesirable environmental effects arising from unnecessary nitrogen use. Successful development of this prediction method would enable more confident use of foliar N by growers and allow more precise decisions of if, and how much, extra N is needed by individual crops in order to meet a specific market requirement for grain protein concentration.

2) Nitrogen strategies for high yielding milling cultivars.

As new high-yielding bread-making wheats are released onto the market, there will be a need for information and advice on appropriate nitrogen management strategies to attain bread-making premiums. In addition there will need to be awareness of the impacts of N:S ratio on grain protein quality. Work is required with these new cultivars to develop nitrogen fertilisation strategies which optimise yield potential without adding to existing environmental problems. This is likely to mean a shift towards nitrogen applications later in the season and there will be a need for information which compares the impacts of soil and foliar applied nitrogen sources at a range of application rates and timings.

3) Improving uptake and recovery of foliar-applied urea-N, and minimising scorch damage.

The potential for improved foliar N recovery is considerable. Several approaches are feasible and practical ways of improving crop uptake and retention of foliar N need to be investigated. This is highly relevant whether foliar urea is applied to aid canopy survival or to boost grain protein. The potential conflict between needing moderate to large rates of foliar N applied at or after the end of leaf development, whilst avoiding the damaging effects of leaf scorch to this crucial leaf layer, needs resolving. Means of improving spray deposition on the crop, minimisation of loss to soil, and aiding retention and uptake on sprayed leaves require research and/or development. New spray technology, i.e. air-assisted spraying and angle of spray nozzles etc., can influence spray deposition patterns and reduce the quantity of spray penetrating to the soil surface. Adjuvants can increase retention of urea-sprays and uptake of urea; this warrants further investigation in association with measures to combat the problem of leaf scorch. Since amendments such as sucrose and calcium compounds can reduce scorch damage, there is scope for further research and development in this area. Variety traits which might affect uptake of foliar N and/or resistance to scorch damage, i.e. leaf orientation and/or leaf cuticle morphology, need investigation.

4) Crops with modified urease or glutamine synthesis rates.

Work on wheat crops with modified rates of urease or glutamine synthetase activity will provide invaluable basic information on N loss pathways associated with foliar N use and may help determine the causes of leaf scorch.

If genetic lines can be successfully developed with decreased urease or increased glutamine synthetase activity, and these are accepted by the market, there will be a need to re-evaluate fertiliser strategies for such crops, and to evaluate the potential for increased use of foliar N fertilisation. This would need to be done in association with measurement of N losses from all sources to identify the most environmentally benign means of crop N fertilisation.

8.0. References

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