UPTAKE AND UTILIZATION OF NITROGEN APPLIED TO THE FOLIAGE OF WINTER WHEAT

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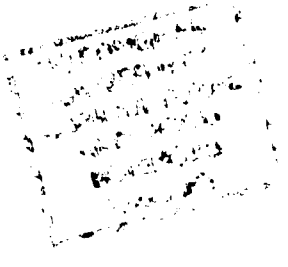

In Memory of my Grandfather

John William Hopkinson 1890 - 1951

ABSTRACT

Foliar urea was applied as a source of late-N between flag leaf emergence and anthesis to winter wheat crops that had received varying rates of basal-N fertilizer in the spring in order to produce crops with differently sized canopies. Canopy size was measured using green area index (GAI). The crops grown were: no N fertilizer applied (N0), conventionally fertilized (Ncf), a Canopy Managed crop grown to a GAI 5 (GAI 5), at IACR-Rothamsted in 1995, with the addition of a GAI 3 crop (GAI 3) at IACR-Rothamsted in 1994 and at Sutton Bonington in 1995.

Each of the applications of late-N as foliar urea resulted in the prolongation of GAI of Canopy Managed crops, irrespective of the timing, amount of N applied, or whether adjuvants were used. The date of complete death of canopy green area was similar for all foliar urea treatments due to the sunny, warm, dry weather at the end of July in both 1994 and 1995, at both sites. The duration of canopy green area was associated with its N content at anthesis, as well as with water availability and the prevailing weather conditions, such that Ncf crops, containing significantly more N than GAI 5 crops at anthesis, retained green area for a longer period than the GAI 5 crops. The application of foliar urea did not always result in an increase in grain yield or quality and the partitioning of biomass and N to the grain was also seemingly unaffected by the application of foliar urea. However, yields from GAI 5 crops receiving late-N as foliar urea, irrespective of the method of application, were not significantly different to those obtained from Ncf crops.

The amount of N deposited and the pattern of deposition were affected by canopy size. Applications made prior to ear emergence penetrated more deeply into the canopy. The top half of the canopy, flag leaf to flag-1 and the ear when present, was the most important site for both N interception and uptake. A maximum of 60 % of the applied N was intercepted by the GAI 5 crops and 10 % remained on the surface of the crop 96 hours later. 35 % of the N 'lost' from the crop surface was taken up over 96 hours. Of the remaining 40 % of the applied N, an estimated 10 % was lost by volatilization, 5 % by drift and 25 % penetrated to the soil surface. N uptake from the leaf surface probably followed an exponential pattern through time. The time for half of the N present initially to be lost ($t_{0.5}$), was unaffected by the side of the leaf to which N was applied, the age of the leaf, growth stage of the plant or the amount of N applied. $t_{0.5}$ was improved only by the addition of a spreader or a penetrant. By harvest up to 64 % of the fertilizer N applied was recovered by the GAI 5 crop of which 87 % was present in the grain. Studies using N^{15} labelled urea suggested that N was transported away from the flag leaf immediately after application, but it was not clear whether N was transported directly to the ear or used in leaf metabolism elsewhere.

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The data presented in Chapter 5 'Results of the field experiment at Sutton Bonington 1995' were collected by Nicholas Broadwith, a BSc Honours project student in the Department of Agriculture and Horticulture, jointly supervised by myself and Dr. David Stokes. The data have been reanalyzed and re-presented.

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Chapter 1: INTRODUCTION

Current research is developing a method for growing smaller crop canopies without a significant yield penalty; this method is known as Canopy Management. Canopies grown by this method are expected to require an input of N late in the season, to maintain canopy green area and to ensure that there is sufficient dry matter and N to fill the grain and maintain quality. This study tested whether foliar urea has a role in these late applications, from flag leaf emergence to anthesis, especially when soil conditions are dry preventing the uptake of soil applied N due to insufficient moisture.

The study has been undertaken as part of a larger MAFF/HGCA LINK funded project "An Integrated Approach to the Nitrogen Nutrition of Winter Wheat", which tested the principles of Canopy Management and developed the method for general use by agronomists and farmers. Within this project the aim of this thesis was to determine the most efficient method of applying foliar urea to canopy managed winter wheat (*Triticum aestivum*) crops.

This introductory chapter details the current and proposed uses of foliar urea within winter wheat production and describes some of the problems that are potentially encountered in its application. The uptake and measurement of foliarly applied urea and the experimental methods used are also discussed. The final section of the introduction summaries the aims of the research programme and the content of the chapters that follow.

1.1 CANOPY MANAGEMENT

Conventional N fertilization practices take into consideration the expected yield and N offtake of the crop and the residual N in the soil from the previous crop. The required fertilizer N is applied either as a single top-dressing or as split applications in March and April; approximately 200 kg N ha^{-1} is normally applied. Due to the diminishing response of wheat to increasing amounts of N applied, this method tends to be an inefficient way of fertilising wheat and physiologically, the process might be made more efficient by matching the applications to the crop's requirement for canopy growth. This could involve applying

smaller amounts of N more frequently but at specific times to produce a canopy of a specific size.

The growth of winter wheat is stimulated by the application of N fertilizers resulting in larger and greener crop canopies, which can intercept more light, enabling more energy to be converted to dry matter and hence yield. In recent years there has been a trend by growers to apply large amounts of N without an appreciation of its effects; excessive applications of N fertilizer can also lead to lodging problems and can increase the incidence of fungal disease, as well as being wasteful, expensive and polluting.

N fertilizer is not used efficiently by winter wheat. On average only 60 % of the applied N is recovered by the crop from the soil (Scott, Jaggard and Sylvester-Bradley, 1994) and half of the applied N is needed to produce the last 10 % of the yield (Scott *et al.*, 1994; Sylvester-Bradley, Stokes and Scott, 1990a). The relationships between crop growth, incident radiation and N, discussed in detail in later sections, forms the basis of the principles of Canopy Management, which aims to reduce the amount of N fertilizer applied in total and improve the efficiency of its use.

Given the current pressures for more "environmentally friendly" farming methods, the European Directive on nitrates and drinking water quality and the likely reduction in subsidies, it is important to examine alternative methods of N fertilizer application in order to reduce losses as well as costs. This method of Canopy Management is yet to be widely adopted within agriculture.

1.1.1 **Principles**

It is well established that for most temperate crops, including wheat, barley and sugar beet, growth rate is proportional to the amount of solar radiation intercepted by the crop canopy (Scott, English, Wood and Unsworth, 1973; Gallagher and Biscoe, 1978; Green 1984 and Sylvester-Bradley, Stokes, Scott and Willington 1990 b). Assuming that water, nutrient supply and disease are not limiting, the growth rate and yield is determined by the radiation intercepted by the crop. The application of N fertilizer can double the yield of grain but it is

often used inefficiently with more than half of the N being used to produce the last 10 % of the total yield. Figure 1.1 illustrates the stepwise relationships between: (from right to left) the N fertilizer applied to the crop and the N taken up, N uptake and canopy size (measured as green area index), canopy size and light interception, light interception and dry matter production (growth) and finally growth and the grain yield and quality. The dotted line relates the amount of N taken up with the quality of the grain produced and therefore the financial output of the system.

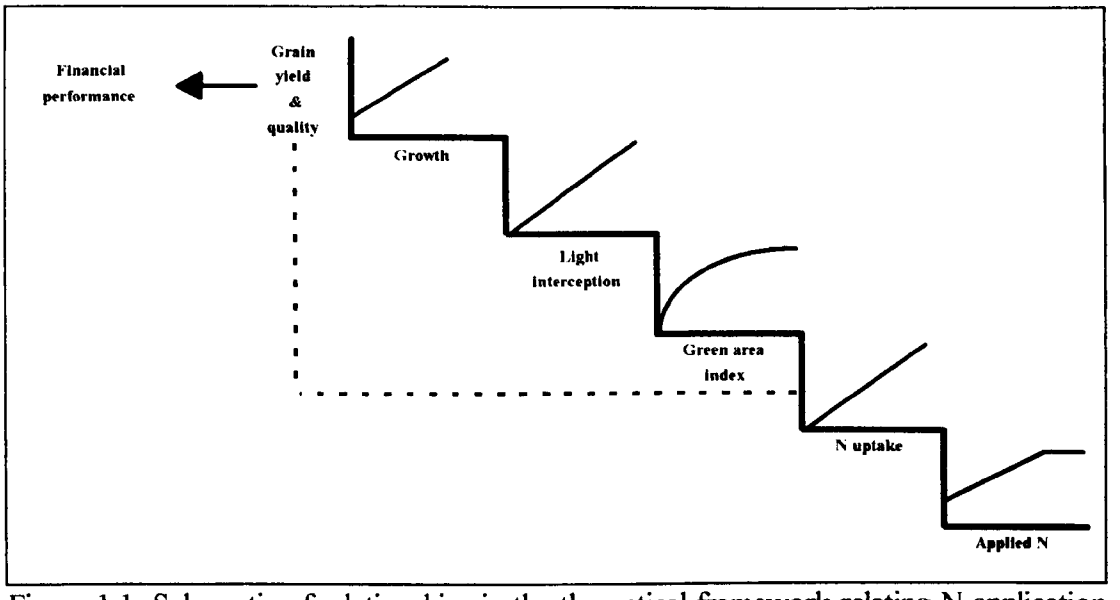


Figure 1.1 Schematic of relationships in the theoretical framework relating N application to yield formation.

Taking each step in turn; Vaidyanathan, Sylvester-Bradley, Bloom and Murray (1987) and Doyle and Holford (1993) suggested that wheat could apparently recover all of the mineral N measured as present in the top 90 cm of soil in the spring and Bloom, Sylvester-Bradley, Vaidyanathan and Murray (1988) estimated that the N applied as fertilizer was taken up with a mean 60 % efficiency, until a point was reached when no further N was taken up. The expansion of the canopy, measured as green area index (GAI - the green area of the crop in hectares per hectare of ground area), is determined by the amount of N taken up by the crop. Canopy expansion in wheat is complete by ear emergence (Stokes, Scott, Sylvester-Bradley, Hopkinson, Milford and Salmon, 1997) and up to this point there is a proportional relationship between the N content of the shoot and GAI with 30 kg N ha^{-1}

producing one unit of GAI (Sylvester-Bradley *et al.*, 1990 b). The proportion of incident radiation intercepted by the crop is governed by the green leaf area and its persistence (Sylvester-Bradley and Scott 1990), the proportion intercepted by the crop canopy is related to the canopy's green area, the appropriate analogy being Beer's Law, which states that the absorption of light by a fluid increases exponentially with depth. This suggests that each increment in GAI with depth into the canopy, intercepts successively smaller additional amounts of radiation (Monsi and Saeki, 1953). Large canopies have the potential to intercept more incident radiation, but may not do so economically in relation to the amount of N fertilizer applied to produce them. Intercepted radiation is converted to dry matter at commonly 1 5 g of dry matter per mega joule (MJ) of radiation intercepted (Monteith, 1977) The efficiency of conversion decreases as green area is lost and photosynthetic activity declines during canopy senescence. The growth of the crop finally produces grain, the quality of which, *i.e.* its suitability for bread making is determined by the amount of N redistributed to the grain (dotted line), indicated by the N harvest index and its concentration in the grain dry matter.

This reasoning suggests that there is an optimum canopy size that is sufficient to intercept most of the incident radiation and contain enough N to sustain canopy function and adequately fill the grain. Crops grown with large amounts of N fertilizer, in excess of 200 kg N ha^{-1}, generally produce canopies with GAIs averaging seven or eight. Although these large canopies intercept about 97 % of the total incident radiation, a slightly smaller canopy of a GAI of 5 can intercept about 90 % and can be produced with a smaller amount of N. On the basis that 30 kg N ha^{-1} produces one unit of GAI, only 150 kg N ha^{-1} would be required in the crop for a canopy of GAI 5, representing a significant saving in N fertilizer. However, there may be a yield penalty in this since there may not be sufficient N in the crop to both adequately sustain canopy function and meet the protein requirements of the grain.

The prolongation of canopy green area could potentially be achieved by late applications of N between flag leaf emergence and anthesis (GS 39 - 65, Zadoks, Chang and Konzak, 1974), mid May to mid June. If soil conditions are dry as is frequently the case at this time

of year, prilled ammonium nitrate applied to the soil would not be readily taken up by the crop, in this situation N applied as foliar urea might be more effective.

1.1.2 Method

A set of canopy management "rules" for N fertilizer applications to winter wheat crops to produce canopies of GAI 5 by ear emergence was devised (Sylvester-Bradley, 1993; Stokes, *et. al.*, 1997). They are as follows:

1. The optimum canopy size for radiation interception is a GAI of 5. To optimise light interception and maximise grain production, this canopy size must be maintained for as long as possible during grain filling.

2. To achieve a GAI of 5, the crop must attain a GAI of 2 by the start of stem extension (GS 31) to provide sufficient shoots for canopy expansion.

3. The mineral N content of the top 90 cm of soil, measured in late February, is assumed to be taken up by the crop with 100 % efficiency.

4. Before the crops reach GS 31, their roots are assumed to be able to extract mineral N from the top 60 cm of soil only.

5. After GS 31, their roots can extract mineral N from the top 90 cm of soil.

6. N in the soil below 90 cm is not accounted for in the calculations and is assumed to be an insignificant proportion of the total soil N available.

7. Applied fertilizer N is recovered with 60 % efficiency.

8. Crop GAI is proportional to the amount of N taken up; 1 ha of green area results from 30 kg of N taken up.

9. After GS 31, the minimum rate of N uptake by the crop was assumed to be 2 kg ha^{-1} day^{-1}. This will allow sufficient time between the last application of N fertilizer for the canopy to reach its maximum size.

10. The minimum amount of prilled ammonium nitrate fertilizer that can practically be applied is equivalent to 30 kg N ha^{-1}.

11. If the soil is dry, foliar N will be necessary to ensure adequate N recovery. It should be applied as an aqueous solution of urea at 30 kg N in 400 l ha^{-1} in two applications of 15 kg N ha^{-1} in 200 l ha^{-1} applied seven days apart in order to avoid leaf scorch.

In the present study, field experiments at IACR-Rothamsted in 1994 and 1995 and at Sutton Bonington in 1995 were set up to test these rules and to analyze the efficiency with which applied foliar urea is used in Canopy Managed crops. A comparison was made between crops grown according to the canopy management rules and conventionally fertilized crops (Ncf). Unfertilized crops (N0) were used to determine the recovery of soil and fertilizer N. This thesis describes the effects of different applications of foliar urea on Canopy Managed crops.

1.2 THE USE OF FOLIAR UREA IN WHEAT PRODUCTION

1.2.1 **N and crop production**

The average N concentration in the crop is between 1.5 % and 4 % depending on the growth stage. N is required in large amounts as it is an important part of amino acids, proteins and nucleic acids. The N content of green plant material consists of approximately 5 % as soluble amino N, 10 % as nucleic acids and 85 % as protein (Mengel and Kirkby, 1987). Over 200 kg N ha^{-1} may be present at harvest in the above ground biomass of wheat. Adequate N supply is therefore important for crop growth, tillering and yield determination.

1.2.2 Why use foliar urea?

Urea is used as a source of N in foliar applications as it has a high N content (46.6%) and can be applied at relatively high concentrations without being phytotoxic (Klein and Weinbaum 1984). Urea molecules are water soluble and highly non-polar (Klein and Weinbaum 1985) with a low salt index and therefore potentially cause only a small change in the osmotic pressure of leaf cells (Gray, 1977). Weseley, Shearman and Kinbacher (1985) found that urea was rapidly absorbed by leaves.

1.2.3 Current uses of foliar urea in crop production

Foliar urea has been applied to winter wheat crops for many years to manipulate yield (Arnold and Dilz 1967) and improve the protein content of the grain. According to Chalmers and Leach (1991) up to half the crops grown for bread making quality grain in England and Wales receive late-N to ensure that the grain achieves the market threshold for protein content. Foliar urea has also been used to supplement spring soil applications, which may not have been used efficiently due to dry soil conditions, to reduce losses by leaching (Readman, Kettlewell and Beckwith, 1993) and to target N applications to specific parts of the crop, *eg* flag leaves and ears (Lawlor, Milford, Mitchell and Mitchell, 1989; Lawlor, Mitchell, Driscoll and Ruffle, 1987). However, applications of foliar urea to fully or partially replace basal soil N fertilizer do not always produce the expected yield benefits, for instance Poulton, Vaidyanathan, Powlson and Jenkinson (1990) observed a reduction of 0.7 t ha^{-1} in yield of both grain and straw. Peltonen, Kittila, Peltonensainio and Karjalainen (1991) found that applications of foliar urea inhibited the development of *Septoria* in spring wheat. Syverud, Walsh, Oplinger and Kelling (1980) thought that the greatest potential benefits were obtained when foliar urea was applied at a specific critical growth stage which required a large amount of nutrients, such as ear formation. However, the response of a crop to foliar nutrition depends upon the amount taken up, the mobility within the plant and the phytotoxicity of the nutrient solution applied (Widders 1991).

1.2.4 Foliar urea and grain protein

Foliar urea has usually been applied to winter wheat between ear emergence and late milky ripe (GS 59 - GS 79). Generally these applications resulted in an increase in grain protein content, but only rarely in yield. Gooding, Kettlewell and Hocking (1991) found that 15 kg N ha^{-1} applied as foliar urea at flag leaf emergence and ear emergence to a number of crops, only produced a yield increase in two out of five cases but the protein content of the grain was improved in four of the crops. Dampney (1992) stated that yield increases should not be expected from late foliar urea applications. However Gooding and Davies (1992), Gooding *et al.* (1991), Smith, Burn and Bartlett (1987) and Sylvester-Bradley, Dampney and Murray (1984) all found that yield increases were produced but usually only when the crop had been insufficiently fertilized earlier in the season, the extra N potentially compensating for under fertilization.

Late applications of foliar urea aim to increase the protein content of the grain above 11%, which is the threshold for suitability for bread making quality grain, (Dampney 1992). A 1% increase in protein content results in an increase of 5% in loaf volume (Salmon 1992), but an increase in N content of the grain may not necessarily improve the quality of the protein. However, late-N as foliar urea has been shown to be more effective in increasing grain N and protein content than applications of prilled ammonium nitrate to the soil (Dampney 1987; Smith *et al.*, 1987 and Dampney and Salmon 1990). 50 kg N ha^{-1} as foliar urea applied at milky ripe stage (GS 75), increased grain protein by 0.6% and 0.8%, (Dampney 1987 and Rule 1987) respectively. The most beneficial time for the application of foliar urea for improving grain protein is the milky ripe stage, GS 75, (Dampney, Salmon, Greenwall and Pritchard 1995; Clare, Spink, Laverick and Bailey, 1993). Morris and Paulson (1985) and Spiertz and Ellen (1978) showed that when applied before anthesis foliar urea promoted yield and reduced the beneficial effects on grain protein. The greatest increases in grain protein percentage have been obtained from applications made close to the end of anthesis (Finney, Meyer, Smith and Fryer, 1957; Pushman and Bingham, 1976; Strong, 1982; Smith, Whitfield, Gyles and Wright, 1989). However, Dampney (1992) and Salmon (1992) concluded that maximum benefit was gained only by application between GS 70 and 75 (early to mid milky ripe) and after GS 79 (late milky-ripe) application was

pointless as the N could not be taken up or assimilated into protein. Generally, the later N was applied the more inefficiently it was used. The response of the crop to late-N as foliar urea is complex and depends upon the N status of both the plant and the soil, the amount of N taken up and the redistribution of N to the grain (Smith, Freney, Sherlock and Galbally, 1991).

Increases in grain protein percentage and baking quality from applications of foliar urea have been shown by Arnold and Dilz (1967), Penny, Widdowson and Jenkyn (1983), Dampney (1987), Grama, Porter and Wright (1987) and Rule (1987). Pushman and Bingham (1976) showed that foliar urea applied at anthesis increased loaf volume over a range of cultivars but this response has subsequently been shown to be dependant upon cultivar (Timms, Bottomley, Ellis and Schofield, 1981).

Increases in grain N content achieved by the application of foliar urea may not necessarily be converted into forms of protein that actually improve bread making quality (Dampney and Salmon, 1990). Rule (1987) found that although foliar urea applications consistently increased grain protein content there was only a small non-significant effect on loaf volume. The grain protein content of wheat is determined by cultivar, climate, soil moisture and nutrient supply, especially the amount of N applied (Grama *et al.*, (1987)). Koch and Mengel (1977) found that 68 - 77 % of the total N taken up by wheat was eventually translocated to the grain and when N supply was abundant, the flow of amino acids was increased, improving the crude protein content. Although late-N will usually increase grain protein, loaf volume can be insensitive to this, as the increase may be too small to affect baking behaviour (Sylvester-Bradley, 1990). Urea was not found on the surface or in the surface layers of the grain after applications of foliar urea (Sylvester-Bradley, Marriot, Hayward and Hook, 1987), excluding the possibility that the urea simply remained on the surface layers of the grain and indicating that the grain itself was protected from direct deposition of spray droplets by the glumes, lemmas and paleas of the ear.

There is an inverse relationship between the percentage protein content of the grain and the yield produced after applications of foliar urea, such that a yield increase causes a decline in protein content (Smith, *et al.*, 1991; Sarandon and Gianibelli, 1990; Grama *et al.*, 1987).

However Grama *et al.* (1987) did show that when foliar urea was applied at anthesis, protein content was increased without a corresponding decrease in yield in some cultivars only and this was related to the differences in the translocation of N and carbohydrates from the vegetative plant parts to the ear.

1.2.5 The role of foliar urea in the maintenance of canopy green area

Although, foliar urea has previously been used merely to improve the protein content of grain, it has the potential to be used earlier in growth to manipulate the size of the canopy by prolonging the duration of the green area and therefore delaying leaf senescence. Foliar applied N may be a more efficient method of supplying N for these purposes than soil applied prilled ammonium nitrate fertilizers, especially during particularly dry soil conditions in the late spring and summer. Cross (1992) and Powlson, Poulton, Penny and Hewitt (1987) found that the recovery of N from foliar applications can be as efficient as from solid soil applied fertilizers.

The application of N changes the expansion rate and size of leaves, it does not greatly alter their rate of appearance or the number of leaves on the main shoot. By the beginning of ear emergence all the leaves of winter wheat have appeared and from this point onwards the persistence of green leaf area is critical in determining grain yield. Sylvester-Bradley, *et al.*, (1990 b) stated that if insufficient N was available during canopy expansion then it was accompanied by death of lateral tillers and the redistribution of their N. Late applications of N have the potential to maintain these tillers in early summer and these are the main contributors to increased GAI.

Once grain fill commences, 20-30 % of the final grain weight is sourced from the remobilization of stored carbohydrates from the green canopy, with continued photosynthesis especially in the flag leaves supplying the remainder. Nitrogen accumulation in the ears is relatively linear and up to 75% of N taken up before anthesis can be remobilized (Sylvester-Bradley and Scott, 1990). N enters the grain as amides or amino acids which are then synthesised to protein within the ear.

Foliar urea has been shown to delay leaf senescence, prolong and increase photosynthetic activity and prevent decline in chlorophyll for about a week when applied after flag leaf emergence but before ear emergence (Lawlor, *et al.*, 1987; Lawlor, *et al.*, 1989). The amounts of protein, chlorophyll and amino acids present in the leaf increased above that of the basal N treatment which did not receive foliar urea. Grain yield and N content of the grain were also significantly increased. However foliar N did not influence the efficiency with which light was used per unit of green leaf area. Garcia and Hanway (1976) used foliar urea to replace N mobilized to the seeds of soya bean, delaying senescence and increasing yield.

1.2.6 **Leaf Scorch**

Applying sufficient N as foliar urea to either improve grain quality or maintain GAI duration should be balanced by the problems of potential leaf scorch, which can lead to yield loss. Dampney and Salmon (1990) applied 120 kg N ha^{-1} of foliar urea as multiple applications of 30 kg N ha^{-1} in 300 l ha^{-1} of water and this resulted in significant leaf scorch of up to 30 % and a yield loss of 0.5 t ha^{-1}. However such dramatic effects are unusual and although leaf scorch is a problem, it usually only causes a 10 % reduction in green area and non-significant yield losses. The earlier the growth stage at which foliar urea is applied, the greater the problem of leaf scorch (Dampney 1992) and it is also exacerbated by warm, sunny conditions (Peltonen, 1993). Poulton *et al.* (1990) found that repeated applications of foliar urea resulted in excessive leaf scorch, reducing the effective GAI and reducing photosynthesis. The accumulation of ammonium from urea hydrolysis can cause leaf scorch by an increase in the pH on the leaf epidermis.

Leaf scorch with foliar urea is usually caused by excessive application rates or highly concentrated solutions. Fertilizer formulations which cause the least foliar damage tend to have a low salt index, causing minimum change in osmotic pressure, are very pure, and have a neutral pH which would not affect leaf metabolism or subsequent uptake (Gray, 1977) who also suggested using small spray droplet sizes to increase coverage and reduce the risk of leaf scorch.

Scorch is caused by the desiccation of cells as spray droplets dry on the leaf surface, Syverud, *et al.*, (1980). Gamble and Emino (1987) suggested that this was caused by the increase in concentration of urea as the solution dried onto the leaf surface before uptake. They observed the formation of a gel-like deposit on the surface of the epidermis of 14 day old maize plants, which caused the epidermal cells to desiccate and collapse and this may provide a mechanism for scorch in which water is lost from the cell into a hydrated deposit on the leaf surface. Damage to epidermal cells eventually caused the plasmolysis of the mesophyll cells.

1.2.7 Light interception and N dynamics

It is well established that leaves grown under high levels of incident radiation contain a greater amount of N than those grown under lower light intensities (Evans, 1989 a, 1989 b; Hirose and Werger, 1987) and that the corresponding nitrogen use efficiency (photosynthetic rate per unit of leaf N) varies in the same way. Lemarie, Onillon, Gosse, Chartier and Allirand (1991) found that in stands of lucerne undergoing self-thinning and regrowth, leaves had a relatively constant maximum N content which decreased as the leaves were displaced to shaded levels. The suggestion was that this reduction in N content was a result of the reduction in the amount of light intercepted by the leaf which may have been related to an adjustment in the photosynthetic capacity of the leaves or senescence. This suggests that Canopy Managed crops may have a more even distribution of N through out the whole of the canopy, unlike the denser conventionally fertilized crops where the lower leaves are predominantly under shady conditions.

1.2.8 N redistribution to the grain during senescence

The major sources of nutrients for grain filling are the leaves and stem, but the remobilization of nutrients from these parts occurs at different rates. Gregory, Crawford and McGowan (1979) showed that leaves were depleted most rapidly during early ear growth and the stems continued to lose nutrients more slowly until harvest. There was little uptake from the soil after anthesis and the total nutrient content of the plant remained relatively constant. Gregory, Marshall and Biscoe (1981) found that as N was translocated

to the grain from the leaves, there was a corresponding reduction in the rate of photosynthesis and suggested that the continued production of dry matter during grain growth depended upon the presence of sufficient N to prevent a decrease in the N content of leaves and therefore photosynthetic rate. Senescence is accelerated in wheat when the plants are water stressed and subject to large evapotranspiration losses (Benbi, 1994).

Harms and Nowak (1990) applied foliar N as a mixture of urea and ammonium nitrate to the flag leaves of wheat at anthesis and found that leaf senescence and the transport of N from the leaf were delayed by 20 days, but the total amount of N taken up into the grain was unaffected. The rate and duration of dry matter accumulation in wheat were not altered by the application of foliar urea at anthesis, grain N content was increased, but this was thought to be attributable to rapid uptake from the foliar applications and not from the prolonged period of grain filling (Sarandon and Gianibelli, 1992). When the size of the ear and therefore the sink strength, was halved (Slafer and Savin, 1994), there were no significant changes in the duration of green area of the wheat canopies, the rate of senescence or the individual grain weight at harvest. It was concluded that the accumulation of soluble carbohydrates in the leaves did not affect the onset or rate of senescence.

Late applications of foliar urea may not therefore have the desired result of prolonging the duration of the green area of a crop or the period of dry matter accumulation but could have the potential to increase the N content of the grain.

1.2.9 Measurements of the chlorophyll content of leaves

The chlorophyll content of leaves has previously been measured destructively following extraction with acetone or similar organic solvents, but recently a SPAD-502 Chlorophyll Meter (Minolta) has become available which allows the measurement of the chlorophyll content of leaves without the need for the destruction of the leaf. This technique was used in the field experiment at IACR-Rothamsted in 1995 to try to non-destructively quantify the decline in green area. It has been tested on a number of crops for use as a tool for determining fertilizer applications.

The Minolta SPAD-502 chlorophyll meter has been used successfully on a range of species such as *Quercus ilex*, the evergreen Oak (Gratani, 1992), *Vitis vinifera*, grape vine(Fanizza, Della, Gatta and Bagnulo 1991), *Zea mays*, maize (Piekielek and Fox, 1992; Dwyer, Anderson, Ma, Stewart, Tollenaar and Gregorich, 1994), sub-tropical fruit trees such as mango (*Mangifera indica*) and lychee (*Litchi chinensis*) (Schaper and Chacko, 1991) and rice (*Oryza sativa*) (Peng, Garcia, Laza and Cassman, 1993; Peng, Laza, Garcia and Cassman, 1995). There is little published work on wheat and other temperate cereals but Monje and Bugbee (1992) found that in wheat the relationship between chlorophyll content measured by extraction and by the SPAD-502 meter, was curvilinear and only gave a good estimate when the chlorophyll content was between 100 and 600 mg m^{-2} (10 - 65 for SPAD-502 meter readings). They suggested that the relationship would be linear only if absorbance of light was dependant solely upon pigment concentration, but it also depended upon light scattering, reflectivity of the leaf and pigment distribution (Vogelmann, 1989). Wood, Reeves, Duffield and Edmisten (1992) found that leaf N concentration in maize was curvilinearly related to chlorophyll content measured by the SPAD-502 meter. The readings obtained from the SPAD-502 meter therefore produced an accurate indication of the chlorophyll content of leaves.

Other authors have related chlorophyll content to the N content of leaves. Shadchina and Dmitrieva (1995) found that there was a direct relationship between the chlorophyll content of the leaves of winter wheat grown in the Ukraine and the uptake of N and accumulation of dry matter. They suggested that chlorophyll content was a better indicator of N uptake from the soil than leaf N content. Filella, Serrano, Serra and Penuelas (1995) stated that chlorophyll content in wheat was mainly determined by N availability. Lopez-Cantarero, Lorente and Romero (1994) worked on aubergine plants (*Solanum* melongena) and showed that the chlorophyll content of leaves were directly correlated with the amount of N and phosphorus fertilizer applied. Tesarova and Natr (1986) showed that N deficient barley plants (*Hordenum vulgare*) had smaller numbers of chloroplasts and contained less chlorophyll than plants that had been grown with sufficient N. When N was replenished, the growth and dry matter accumulation were increased and the chlorophyll content and chloroplast number increased but did not achieve the levels of plants that had not been deficient in N.

In this study, the SPAD-502 chlorophyll meter was used to provide an indication of the chlorophyll content of the flag leaves and through this an indication of their N status. It was used to measure the decline in green area of the plant canopies at IACR-Rothamsted in 1995.

1.3 UPTAKE OF FOLIAR UREA

1.3.1 **Volatilization and urease activity**

The break down of urea to ammonia and carbon dioxide by the action of the enzyme urease is well documented (*e.g.* Andrews, Blakeley and Zerner, 1984) and the subsequent volatilization of the ammonia gas can be a major source of loss of foliarly- applied urea. Sometimes more than 50 % of the applied urea is lost by this means (Bremner, 1990). Bowman, *et al.* (1987) measured volatilization losses during the first 24 hours after the application of foliar urea to bluegrass turf, (*Poa pratensis*), to be as high as 35 % of the applied N. There were only small losses after this time and they suggested that the relatively short time over which volatilization occurred was related to the rapid uptake of urea by the plant. Weseley, Shearman, Kinbacher and Lowry (1987) showed that high moisture levels on leaves promoted urea hydrolysis and any subsequent drying promoted ammonia volatilization by concentrating the urea and increasing the pH of the water film.

When foliar urea was applied to the surface of leaves of Italian ryegrass (*Lolium multiflorum*) it stimulated the multiplication of phylloplane bacteria causing an increase in the number of ureolytic organisms and consequently an increase in urease activity in the first 24 hours after application (Hoult and McGarity, 1989). However the presence of ammonium after the hydrolysis of urea suppressed the activity of the urease enzymes and De Turk (1955) showed that ammonium assimilation by the bacteria occurred in preference to urease synthesis. Hoult and McGarity (1989) also found that as the ammonium concentration declined the urease activity recovered and this reduction in ammonium concentration could be attributed to volatilization and utilization by the bacteria, and probably to uptake into the leaf. Hogan, Swift and Done (1983) suggested that ammonia toxicity could result from high levels of urease activity if the ammonia produced was not

assimilated quickly. Urease inhibitors applied with urea fertilizer may be able to reduce the amount of N lost by volatilization (Rogers, Penny, Widdowson and Hewitt, 1987).

1.3.2 **Urea uptake**

Bowman and Paul (1992) showed that 40 % of the urea applied to ryegrass was absorbed after 24 hours). The concentration of urea in the leaf reached a maximum between 12 and 24 hours after application and then declined; after 12 hours, there were larger amounts of ammonium than urea present indicating that there was rapid hydrolysis of urea. Bowman and Paul (1990 a) found that most N was absorbed in the first 12 hours by tall fescue and creeping bent grass turf, 35-55 % of the applied N was absorbed in total and old leaves and growing shoots were the predominant sink for the N. The same pattern was observed by Bowman and Paul (1990 b), Bowman and Paul (1989), Bowman, *et al.*, (1987), Klein and Weinbaum (1984 and 1985), Weseley *et al.* (1985), Below, Crafts-Brander, Harper and Hageman (1985) and Morris and Weaver (1983). Holloway, P.J. (personal communication) suggested that half of the applied N could be taken up within 12 hours of application.

Uptake and subsequent metabolism of foliar applied urea has been shown to be rapid, Turley and Ching (1986 a). Within four hours of application, forty-four times and eight times more urea and ammonia respectively were present in the leaves of barley than was present initially. Turley and Ching (1986 b) found that there was a corresponding increase in the *in vivo* activity of urease and nitrate reductase and it is thought that urea was broken down by urease to ammonia and then assimilated into proteins. Chen and Ching (1988) found that the endogenous urease activity of a barley leaf had increased twenty times, one hour after the application of foliar urea and there was a corresponding increase in the urea content of the leaf. The urea content peaked one hour after spraying and decreased to control level after five hours. The application of foliar urea resulted in urea being taken up rapidly and the synthesis of urease enzymes was induced.

Lawlor *et al.* (1987) found that urease activity increased with increasing leaf age and was also dependant upon the position in the leaf, usually being greatest at the active growth

points (Volk and McAuliffe, 1954). Uptake has been found to be greater in younger leaves, Cain (1956) and Robertson and Kirkwood (1969), who suggested that this was caused by the thickening of the leaf cuticle and increased deposits of cutin and wax. Klein and Weinbaum (1985) found that uptake by younger leaves was around three times greater than by older leaves but the rate of uptake declined more rapidly in young leaves. This may be related to the findings of Cook and Boynton (1952), Klein and Weinbaum (1985) and Klein and Zilkah (1986) who all found that retention of solutions on the adaxial (upper) surfaces of leaves were approximately one third to one fifth that on the abaxial (lower) surface. Cain (1956) showed that urea was absorbed much more rapidly when applied to the lower surface of coffee leaves (*Coffea arabica*) and this was also described by Franke (1967), who stated that uptake was always greater over the lower leaf surface as there were more stomata present.

Between 62-64 % of N^{15} labelled foliar urea applied to winter wheat crops at IACR-Rothamsted was recovered in total at harvest (Powlson, *et al.*, 1987; Powlson, Poulton, Moller, Hewitt, Penny and Jenkinson, 1989); 60 kg N ha^{-1} was applied at anthesis and the total recoveries from applications at earlier or later growth stages were much lower. Altman, McCuistion and Kronstad (1983) found that 44 % of N^{15} was recovered in the grain and similar amounts were found to be present in the grain by Powlson *et al.*, (1987) and Powlson *et al.* (1989). The dominant sinks for N^{15} in wheat are the leaves and grain, to which N^{15} was readily translocated. N from foliar urea is thought to enter more readily mobilized pools of N, than that derived from soil applications, as N taken up into the leaves of maize was quickly transported to the grain from both pre and post anthesis applications and not stored in the stalks (Below *et al.*, 1985).

1.3.3 Mechanisms for urea uptake

Uptake has been shown to be greater across the abaxial (lower) surface of the leaf, (Klein and Zilkah, 1986; Klein and Weinbaum, 1985 and Cain, 1956). There are generally a greater number of stomata present on the abaxial than the adaxial leaf surface, the cuticle covers the stomata: the main walls of the atrium, central pore and air spaces. Stomata have previously been thought to be the major point of uptake for foliarly applied nutrients but the

solution droplets are prevented from entering via the stomata as the stomatal pores are gas filled, which cannot be displaced by liquids except under high pressures. Therefore the cuticle is the main barrier to the uptake of foliar urea, (Leon and Bukovac, 1978; Yamada, Wittwer and Bukovac, 1964 a). Yamada, Wittwer and Bukovac (1964 b) found that the cuticle was negatively charged and that there was a gradient from low polarity on the exterior of the cuticle to a relatively high polarity on the layers bordering the epidermal cell walls. Franke (1967) found that this negative charge was neutralized by cations which easily bound to it. Franke (1986) found that there was a concentration gradient across the cuticle and the cell wall which was required for the penetration of the cuticle.

The cuticle consists of cutin which is water repellent. Cutin is made up of polyhydroxy fatty acids, in which the hydroxyl groups in the molecules are esterified with carboxyl groups. These are free-forming groups producing a structure with intermolecular spaces, which facilitate the passage of water molecules and dissolved substances, even though these spaces are small in diameter. The cuticle has a wax coating which is highly water repellent, (Franke, 1986). The external wall of the epidermal cells, beneath the cuticle, is a mixture of cellulose, pectin, hemicellulose and wax, structured as interlinked fibrils. It is permeable to water and any substances dissolved in water. The interfibrillar spaces vary in size, some are up to 0.01 μm in diameter.

The lipid character of the cutin and wax layers of the cuticle prevents penetration by hydrophillic substances (Franke 1967) and the greater the waxiness of the leaves the less the adherence of aqueous spray molecules (Robertson and Kirkwood 1969). A large contact angle for spray droplets such as that on young wheat plants and mature lupins reduces the ease with which the leaf surface is wetted (Robertson and Kirkwood 1969). Foliarly applied urea must, therefore, be taken up via the cuticles of epidermal cells (Franke, 1986). Yamada, Rasmussen, Bukovac and Wittwer (1966) found that ions only pass through discrete areas of the cuticle and that urea was bound similarly on both the inner and outer surfaces of enzymatically isolated cuticular membranes. It has been suggested that the increased rate of urea uptake across the cuticle compared with the uptake of ammonium or nitrate ions is due to the fact that small, uncharged molecules are taken up more readily than ions (Marschner, 1986).

Diffusion is the main mechanism for the penetration of the cuticle (Holloway, P.J. personal communication), a concentration gradient is formed which allows the urea to penetrate the cuticle. However, there is some evidence for facilitated diffusion as the mechanism of uptake of foliar urea, which occurs via a change in the structure of the cuticle membrane (Yamada, 1962). Yamada also found that urea greatly accelerated the penetration of cations and anions through cuticular membranes but this has not been investigated subsequently. Once a substance has penetrated the cuticle it must then cross the cell wall and the plasmalemma. Cell wall penetration is thought to occur in special epidermal areas and through separated pathways of ectodesmata. Uptake across the plasmalemma is an active process and in uptake by root cells is usually the rate limiting step, however in foliar nutrition it is the diffusion of the nutrient across the cuticle and through the cell wall that limits uptake (Mengel and Kirkby, 1987).

The rate of penetration of the cuticle depends primarily on the thickness of the cuticle, its surface area and the amount of wax present. Leon and Bukovac (1978) found that the cuticle was thicker on the adaxial surface of olive leaves (*Olea europaea*) , the surface was fairly smooth compared to the abaxial surface which had a thinner cuticle that was rough, with ridges and depressions increasing the surface area of the leaves over which diffusion could occur. Older leaves tend to have greater deposits of wax which repel water (Robertson and Kirkwood, 1969), preventing the formation of thin layers of the aqueous nutrient solution on the leaf surface and reducing the potential for uptake.

1.3.4 **Measurement of urea uptake**

It is important to be able to differentiate between measurements of N present on the external surfaces of the plant and that present internally. The uptake of foliar urea by leaves has been studied using three different methods: washing the urea from the surface of the leaf, leaf tissue analysis for N content and N^{15} labelled urea.

Removing urea by washing it from the leaf surface at different times after spraying measures the amount of urea that remains on the exterior surfaces of the foliage. This method has been employed by Cook and Boynton (1952) on apple leaves (*Malus pumila*);

Cain (1956) on coffee (*C. arabica*), cacao (*Theobroma cacao*) and banana (*Musa sapientum*) and Impey and Jones (1960) on Navel orange leaves (*Citrus sinensis*). All used distilled water to remove the urea and were only partially successful in recovering what was applied, in all cases less than half was recovered. Klein and Weinbaum (1985) and Klein and Zilkah (1986) used 0.1 % solutions of the surfactants Triton X-100 and L-77 and recovered 90 to 95 % of the applied urea. Measuring the change in the N content of the plant tissues was a more uncertain method of recording the uptake of urea as it is more variable, but has been used with reasonable success by Weseley, *et al.* (1985) on turf grass.

N^{15} labelled urea has been used by Volk and McAuliffe (1954) on tobacco (*Nicotiana tabacum*); Vasilas, Legg and Wolf (1980) and Morris and Weaver (1983) on soya beans (*Glycine max*); Below, *et al.* (1985) on maize (*Z. mays*); Beringer and Koch (1985) on sugar beet (*Beta vulgaris*); Karasuyama, Yoneyama and Kobayashi (1985) on tea (*Camellia sinensis*); Klein and Weinbaum (1985) on almond (*Prunus amygdalus*) and olive (*O. europaea*); and Widders (1991) on tomato (*Lycopersicum esculentum*). Shelp and Shattuck (1986) and Freiberg and Payne (1957) used C^{14} labelled urea on tomato fruits. All found that a reasonable estimation of N uptake was obtained from the methods they used.

Bowman and Paul (1990 a) and Bowman and Paul (1989) tested these methods on tall fescue (*Festuca arundinacea*) and creeping bent grass turf (*Agrostis palustris*). They concluded that the tissue N method lacked sensitivity due to the large variability in the results and the lack of repeatability and that washing the urea from the leaf surface gave a similar estimate of urea uptake to more direct measurements made using N^{15} labelled urea.

All three of these methods were tested in the present study. Urea was washed from the surface of the crop and the corresponding changes in tissue N content measured. A separate N^{15} study was undertaken to determine the fate of the foliar urea once it had been taken up by the plant.

1.4 SPRAY APPLICATION

1.4.1 **Canopy structure and spray deposition**

The deposition of spray droplets onto the canopy is a combination of sedimentation and inertial impaction. The latter dominates when clouds of droplets fall onto the canopy. The former is determined by the area and orientation of the foliage. The vertical distribution of spray depends upon the rate at which the droplets are trapped (this is related to the density of the canopy and the orientation of the foliage) and the rate of vertical transport into the canopy (Bache, 1985). As a spray comes into contact with the canopy, the droplets are trapped or filtered out and the airborne concentration reduced. Generally smaller droplets (less than 100 μm in diameter) will improve the retention of a spray onto cereals and the deposition onto the underside of the leaf. Knoche (1994 a), found that in wheat, smaller droplets (less than 150 μm in diameter) increased the performance of a herbicide. Larger droplets will settle on the upper part of the canopy and not penetrate into it. The deeper the penetration into the canopy the greater the reduction in coverage of the target crop (Gohlich, 1985). Sprays are applied using different sizes of nozzle to produce sprays of different quality, determined by the volume median diameter of the droplets produced. These are: coarse > 401 μm, medium 201-400 μm and fine 101-200 μm (Matthews, 1982).

The variability of spray deposition onto crop targets is well known. Finer droplets increase the coverage of the plant material when applied at low pressures and speeds, but the variation that occurs between trials can obscure differences in the performance of compounds (Grayson and McCarthy, 1987). Grayson and McCarthy (1987) carried out extensive tests to examine the variation in spray deposition, highlighting five main sources of variation: a) between spray formulations, b) between replicate plots, c) within plots, d) between parts of plants and e) interaction between the parts of a plant and the position within a plot. The variation in deposition was large for any point within in a plot, (the standard error may be as much as 50 % of the mean volume deposited), the size of this variation was liable to mask any patterns of deposition. The variation between plots (15 - 31 %) was thought to be caused by the spraying operation itself and the exact environmental conditions at the time of spraying, particularly sudden wind changes.

Variation within a plot was less clear, as variation between shoots at the same position in the plot was small, but was thought to be related to variation in the height and speed of travel of the boom over the plots and to any turbulence within the plot caused by breezes. Elliot (1991) using a fluorescent dye studied the deposition from a small track sprayer on wheat ears and artificial targets found that the major source of variation was the output from the nozzles on the boom.

There is obvious variation in the amount of spray deposited on the different organs of the plant and these differences are usually highly significant. Deposition is related to the surface area of the target, its angle and the position in the canopy. Lower leaves can be shaded from the spray, therefore deposition depends upon the angle of the incident spray, which also affects the deposition onto the ears. The size of the catchment area presented to the spray is also a factor. Grayson and McCarthy (1987) using a gentian violet marker, reported that 65 % of the total spray intercepted by the crop was deposited onto the flag leaf, 22.5 % on flag -1 and 12.5 % on the ear. They did not find much deposition below the flag -1 level. Bache (1985) found that deposition depended upon the density of the canopy. In a dense canopy, 72 % of the applied spray was intercepted within the top 40 cm (including the ear, flag leaf and flag -1), but only 57 % was intercepted within this layer in a more open canopy. More of the spray was intercepted in total by the open canopy, there was greater penetration of spray to the bottom 80 cm of crop and more of the spray was deposited onto the soil, (8.2 % and 2.2 % for the open and dense canopies respectively). Taylor and Anderson (1987) confirmed this, as at GS 85 (when the canopy was almost dead) virtually no spray solution penetrated to soil level.

The deposition onto particular parts of a leaf depended upon its orientation, smaller amounts of spray tended to be deposited on the basal section of the leaf if it was shaded by the stem and more vertically orientated leaves tended to have more spray deposited onto the tip section than leaves that were inclined more horizontally (Koch and Spieles, 1992). However, the mean deposition onto bent or horizontal leaves was greater than onto vertically orientated ones.

Sylvester-Bradley, Rochford and Rule (1990) investigated the possibility of physically parting the canopy when spraying with urea to accentuate the deposition onto lower leaves, to help reduce the extent of scorching on the upper photosynthetically active leaves and, by targeting lower leaves during grain fill, to aid the redistribution of N to the grain. Yield was increased by around 0.3 t ha^{-1} both with and without urea spray and no leaf scorch was recorded, but parting the canopy gave little improvement in N uptake.

1.4.2 Spray drift

The application of liquid sprays to crop canopies is a highly variable process and the efficiency of application is affected by many different factors. The main sources of loss are evaporation of the active ingredient and spray drift. However, hydraulic flat fan nozzles, which were used to apply foliar urea in the field experiments described in subsequent chapters, have been shown to produce the most even pattern of spray deposits (Cooke, Hislop, Herrington, Western, Jones, Woodley and Chapple, 1986). It has been suggested that a maximum of 5 % of the spray can be lost by drift, a more usual figure is 2 - 3 % (T. Robinson, personal communication).

Spray drift is a highly complex process which is affected by many variables such as droplet size, wind speed, atmospheric conditions and the application pressure of the spray. Small droplets, less than 100 μm in size, quickly lose their initial momentum after leaving the nozzle and become more susceptible to the local atmospheric turbulence. This is caused and affected by wind speed, the speed of travel of the vehicle on which the sprayer is mounted and the oscillations of the boom itself. Smaller droplets, increased wind speed and turbulence all result in a greater risk of spray drift. An increase in the operating pressure of the sprayer can also increase drift, as it reduces the droplet size distribution of the spray, with a larger number of smaller droplets being produced. However there must be a trade off between droplet size and coverage of the crop, as smaller droplets result in a better coverage of the plant material but larger droplets reduce the risk of drift. The condition of the crop itself also contributes to the amount of spray lost through drift, as with increasing crop height and size, a larger surface area is presented to the sprayer which intercepts the spray more efficiently than smaller, shorter canopies. With increased crop height there is

also an increase in wind velocity, resulting in more turbulence over the crop surface which increases the dispersion of the spray and therefore drift (Hobson, Miller, Walklate, Tuck and Western, 1993; Nordbo, Kristensen and Kirknel, 1993).

1.4.3 The use of adjuvants in spray applications

The usefulness of adjuvants in the application of foliar urea and agrochemicals has long been established. Franke (1967) suggested that absorption was increased by wetting the leaf surface to enable penetration of urea. Cook and Boynton (1952) found that the addition of wetting or spreading agents improved the absorption of nitrogen at the surface of the leaf. However, the ability of a liquid to wet a surface depends on the nature of the surface and the surface tension of the liquid (Boynton, 1954). Choi, Ikeda and Yamada (1989) found that the application of sucrose-fatty acid esters increased the absorption of urea by senescing tomato and maize leaves by successfully reducing the surface tension of the droplets and spreading them into a thin film and thus improving uptake.

There is a vast literature on the use of the large number and types of adjuvants available and there are many conflicting citations on the effectiveness or otherwise of particular products. An adjuvant does not necessarily produce the same effect on different species. Kirkwood (1994) summed this up: the activities and effects of adjuvants are specific to the compound and the target plant species. Adjuvants are applied to improve the retention of the active ingredient, alter the droplet size distribution and increase the amount taken up by the plant (Permin, Jorgensen and Persson, 1992). There are several different types of adjuvants. Wetters or spreaders lower the surface tension of the water, flattening the spray droplet so that it spreads more evenly over the leaf surface providing a greater surface area for uptake, but increasing the potential loss by evaporation. Stickers or extenders can improve rain-fastness and persistence of chemicals on the leaf and can also slow the breakdown of some pesticides. Penetrants act as carriers for the diffusion of the active ingredient across the cuticle, for example the penetrant LI-700 temporarily opens the surface of wax particles. Vegetable and mineral oils acts as carriers of the active ingredient and reduce the loss by evaporation by coating the water droplets.

Three types of adjuvant were tested in the present study, a spreader Silwet L-77, a penetrant LI-700 and a sticker Spray-Fix (Newman Agrochemicals, Cambridge). There are no references to the action of Spray-Fix in the literature. LI-700 is the most widely used penetrant and has been tested on a variety of crops with a large number of agrochemicals. Its effects have been found to be variable depending upon the crop and the active ingredient with which it was tested, but when applied to winter wheat with the growth regulator chlormequat, LI-700 was found to improve the number of grains produced and reduce the length of lower internodes more than when chlormequat was applied alone (Green, Jones and Chalmers, 1993).

Silwet L-77 has been found to improve both stomatal and non-pore infiltration of leaves by the active ingredient (Omokawa, Takeuchi and Konnai, 1993) and is thought to be less phytotoxic than other adjuvants (Stevens, Gaskin and Zabeiwicz, 1988). Silwet L-77 is an organosilicone surfactant with a low surface tension, assisting retention and increasing coverage (Stevens and Zabeiwicz, 1990). Stevens and Zabeiwicz (1990) found that a spray solution containing Silwet L-77 could infiltrate stomata more effectively and improve the rain-fastness of an active ingredient. Buick, Buchan and Field (1993) and Stevens (1993) found that it lowered the surface tension of the solution sufficiently to allow stomatal infiltration to occur and Knoche (1994 b) suggested that the mechanism for entry via the stomata was mass flow.

1.5 AIMS OF THE RESEARCH PROGRAMME

The aims of this study were to clarify the dynamics of deposition and uptake of urea by wheat from foliar applications and to assess the effects of these applications on the green area duration, yield and grain quality of Canopy Managed crops.

The individual aspects of the study are shown in Figure 1.2. This illustrates (from top to bottom) the factors that affect the deposition of urea onto the leaf surface, the uptake by the plant, the steps that can be taken to potentially improve uptake, the fate of the N within the plant after uptake, the effect of the foliar applications on the prolongation of green area and the effect on yield and quality of the grain produced.

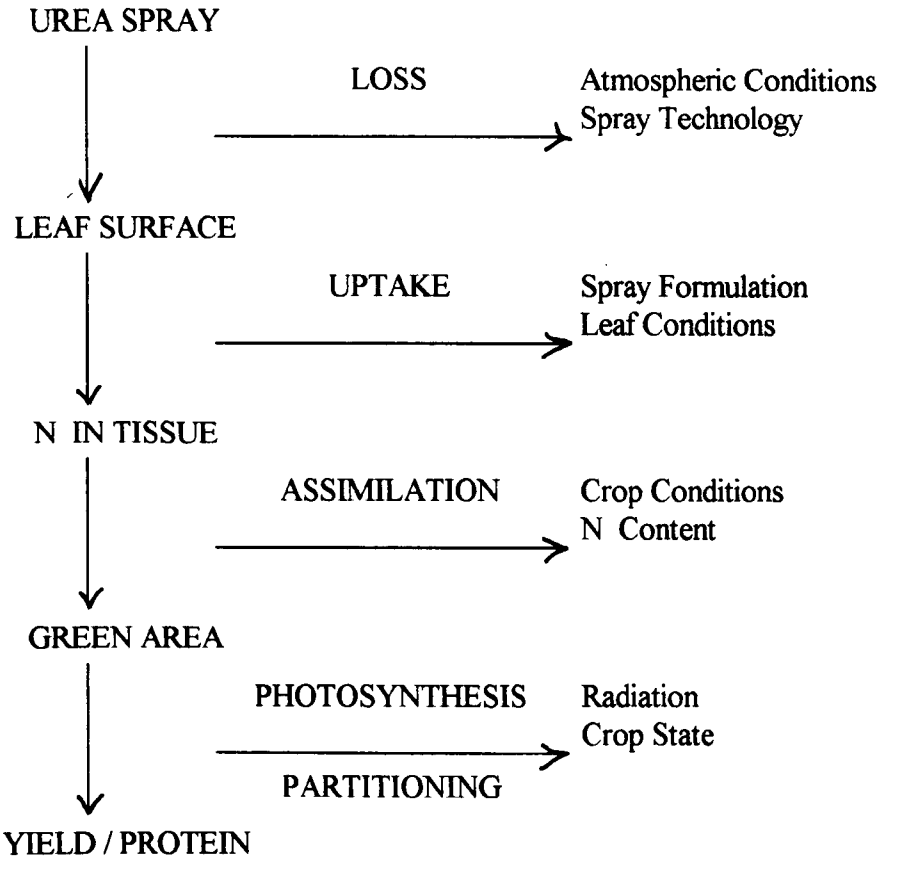


Figure 1.2 The relationships between the factors affecting the deposition and uptake of foliar urea, which are examined in this study.

The general materials and methods used are stated in Chapter 2. Chapters 3, 4 and 5 describe the results of field experiments carried out at IACR-Rothamsted in 1994 and 1995 and at the University of Nottingham farm at Sutton Bonington in 1995, reporting the agronomic effects of the foliar urea treatments applied. These chapters relate to the assimilation and partitioning of the N taken up by the crop and the effects on green area, yield and grain quality. Chapter 6 reports the deposition and uptake of N from foliar urea applications made in these experiments. The studies carried out under controlled environment conditions, including the N^{15} experiment are described in Chapter 7. These two chapters aim to quantify the amount of urea deposited onto crop canopies, the behaviour of the urea once present on the leaf surface, the dynamics of N uptake by the crop and the factors affecting this, such as the use of adjuvants, the age of the leaf and the side of the leaf to which foliar urea was applied. These variables are described in the first

three steps of Figure 1.2. The results and the conclusions that can be drawn from them are discussed in the final chapter, Chapter 8.

The main hypothesis tested by this study was: the application of foliar urea is an efficient method of applying N late in the season to Canopy Managed crops. This hypothesis was tested by examining the affects of foliar urea upon the duration of canopy green area, the yield and quality of the grain obtained. The utilization of foliarly applied N and the efficiency of uptake were also examined.

Chapter 2: MATERIALS AND METHODS

2.1 FIELD EXPERIMENTS

Field experiments were conducted at IACR-Rothamsted, Hertfordshire, during the years 1993/1994 and 1994/1995 and at the University of Nottingham Farm, Sutton Bonington, Leicestershire, in 1994/1995. At each site a range of basal N treatments was applied to which extra late-N treatments as either foliar urea or soil applied ammonium nitrate were superimposed.

The experimental winter wheat crops were established on soil with non-limiting phosphorous and potassium contents and the variety Mercia was sown at a rate of 380 seeds m^{-2} in all three experiments. The soil at IACR-Rothamsted was a flinty silt loam / loam over clay with flints of the Batcombe series and at the University of Nottingham Farm, Sutton Bonington there was an alluvial soil of the Fladbury series. The details of seed bed preparation, other agronomic actions and the management of weeds, pests and disease are summarised in Appendix 1.

2.1.1 **Basal spring nitrogen treatments**

Basal spring N applications were made to provide crop canopies of contrasting size under four basic treatments, of which two were grown using the strategy of canopy management (section 1.1)

Ncf A conventionally fertilized crop of normal spring applications of N, as judged on the basis of local information so that the crop had sufficient N but was at minimal risk from lodging.

N0 Spring N was not applied

GAI 5 N fertilizer applied to produce a canopy with a green area index of five by ear emergence (GS 59).

GAI 3 N fertilizer applied to produce a canopy with a green area index of three by ear emergence (GS 59).

A combination of some or all of these treatments were used in the three experiments. The basal N applied to the GAI 5 crops was determined using the rules listed in 1.1.2, and were suitably modified to produce crops of GAI 3.

2.2 METHODS OF MEASUREMENT

2.2.1 **Growth Analysis**

2.2.1.1 *IACR-Rothamsted 1994*

The crops were sampled at fortnightly intervals during growth. The first sample was taken on 21 March 1994 before the start of stem extension (GS 30) and before the first application of N fertilizer. An area of 0.804 m^2 (0.67 m by ten rows) was sampled on each occasion. The first four samples involved the removal of the whole plant including the roots, which were washed to remove any soil present and the whole sample then thoroughly dried. Total plant and shoot number was determined, the roots removed and the projected area of the plant material measured using a Delta-T planimeter, (section 2.2.2). Dry weights were determined after drying for a minimum of 16 hours at 80 °C to reach a constant weight. In later samples, from flag leaf emergence (GS 39) onwards, the shoots were cut off just above soil level, shoot number and GAI was determined. All samples taken for growth analysis were milled and analyzed for total N content, (section 2.2.6).

2.2.1.2 *IACR-Rothamsted 1995*

Destructive growth analysis samples were taken at tillering (GS 22), the start of stem extension (GS 30) and prior to ear emergence (GS 49). An area of 0.804 m^2 (0.67 m by ten rows) was sampled by removing the whole plant at GS 22 and cutting the plants off

above the soil surface for the other two samples. On each occasion shoot number, GAI and dry weight were determined. The samples taken at tillering and stem extension were milled and analyzed for total N content.

2.2.1.3 *Sutton Bonington 1995*

Samples were taken on two occasions, the first on 18 May at flag leaf emergence, prior to the application of the foliar urea treatments and the second on 14 July to assess the decline in the green area of the canopies. An area of 0.72 m^2 was sampled using a quadrat, the shoots were cut off at soil level and GAI, shoot number and biomass determined. The samples were subsequently milled and analyzed for total N content.

2.2.2 **Measurement of green area**

The green area of all the plant samples taken was determined using an automatic planimeter, (Delta-T, Cambridge). Plant material was placed on a conveyer belt which passed under a camera producing black and white pictures. The pixels blacked out by the plant material were counted by the machine and the value calculated for the area as cm^2. The machine was calibrated using a strip of metal of a known area.

2.2.2.1 *Visual assessment of green area*

Daily, visual assessments were made of the percentage of the canopy that remained green at IACR-Rothamsted, from 17 July to 27 July 1995.

2.2.2.2 *SPAD chlorophyll meter measurements*

A hand held Chlorophyll Meter SPAD-502 (Minolta, Japan) was used to measure the chlorophyll content of the flag leaves at IACR-Rothamsted in 1995. The results obtained provided an indication of the chlorophyll content of the leaf but not a measure of its green area.

The meter uses the principle of optical density difference over two wavelengths. The values produced by the meter correspond to the amount of chlorophyll present in the leaf, calculated from the amount of light transmitted by the leaf in two wavelength ranges where the absorption of light by chlorophyll is different. The first range, visible red light (600-700 nm) where absorption is high and is not affected by carotene and the second, the infra red range (860-1100 nm) where absorption is extremely low (Minolta Camera Co. 1989). Two light emitting diodes emit light in sequence through the leaf which enters a silicon photodiode receptor recording the amount of light absorbed and this is used to calculate a SPAD value.

Mean values for each replicate plot were obtained from 30 readings taken on individual flag leaves, one measurement per leaf. Readings were taken by placing the measuring head in the middle of the leaf lamina taking care not to place it over the midrib and to keep it away from the leaf tip.

2.2.3 **Hand harvest - components of yield**

2.2.3.1 *IACR-Rothamsted 1994*

An area of crop 1.2 m^2 (1 m by 10 rows) was sampled, the shoots were cut off above soil level, placed in a hessian sack, and hung up to dry under cover for approximately one week. The total fresh weight of the sample was recorded, and then it was threshed and the weight of grain, chaff and straw determined. The dry weight of grain, chaff and straw was recorded after drying at 80 °C for at least 16 hours and calculated as both 85 and 100 % DM (t ha^{-1}).

2.2.3.2 *IACR-Rothamsted 1995*

100 stems were taken at random from the plot, placed in a hessian sack and then hung up to dry for one week. The samples were threshed and the dry weight and yield of the grain, chaff and straw determined.

2.2.3.3 *Sutton Bonington 1995*

A 0.72 m^2 area of crop was harvested, the ears removed and weighed and then threshed using a stationary threshing machine. The dry weight of grain, chaff and straw was determined.

2.2.4 Combine harvest

2.2.4.1 *IACR-Rothamsted 1994*

Yields were measured on an area of 0.003 ha (10 m x 3 m) using a plot combine. A 3 kg sample of grain and a 1.5 kg sample of straw were taken. These were sub-sampled for the measurement of total dry weight (t ha^{-1}) at 85 % DM and grain quality measurements.

2.2.4.2 *Sutton Bonington 1995*

An area of 0.006 ha (4 m x 15 m) was harvested using a plot combine and sub-samples of grain were taken for measurement of total dry weight (t ha^{-1}), thousand grain weight (g) and N content.

2.2.5 Grain quality

2.2.5.1 *Grain size and weight*

Grain samples were passed through a series of sieves of mesh size 3.5 mm, 2.2 mm and 1 mm. The proportion of grain retained by each sieve was determined by weight and any pieces of broken grain and chaff removed. The number of grains in the cleaned, weighed, sieved sample were counted and thousand grain weight calculated.

2.2.5.2 *Measurement of Hagberg falling number*

Hagberg falling number is used as a standard method for the determination of alpha-amylase activity in grain and therefore as an indicator of bread making quality. The procedure was carried out using Falling Number Apparatus Type 1400 (Falling Number AB, Sweden). A suspension of flour was rapidly gelatinized in a boiling water bath and the liquefaction by alpha-amylase of the starch contained in the sample measured by the time taken for a metal stirrer to drop through the suspension.

The grain samples were ground to pass a 0.8 mm mesh and the moisture content of the sample determined using a moisture meter. 7 g of milled grain was added to 25 ml of distilled water at 22 °C ± 2 °C in a viscometer tube, a dry stopper was placed on the top of the tube and then it was vigorously shaken 20 - 30 times to produce a homogeneous suspension. Any solid adhering to the surfaces of the tube was then scraped into the suspension. When mixing was complete the tube was immediately placed in the boiling water bath and the stirring mechanism attached within 30 seconds of mixing being completed. The mixture was automatically stirred for 60 seconds and then the viscometer stirrer was released to sink under its own weight through the gelatinized suspension. Falling number was defined as the total time in seconds from the immersion of the viscometer tube into the water bath to the point at which the viscometer stirrer had fallen the prescribed distance through the gelatinized suspension.

2.2.5.3 *Specific weight*

The specific grain weight or hectolitre weight, was measured using a chondometer (Garungsgewerbe, Berlin, Germany). A graduated cylinder was filled with grain to a marked point and then poured into the top of the chondometer. A metal plate was removed allowing a weight and the grain above it to fall, when the weight reached the bottom of the chondometer the metal plate was reinserted and any grain remaining above it was discarded. The weight of the grain that had fallen was recorded, and this figure was converted to give a value for the specific weight as (kg hl^{-1}).

2.2.6 **Analysis of nitrogen in plant tissue**

The total N content of the plant samples was analyzed using a LECO CNS 2000 Automatic Combustion Analyzer which employs a modified version of the Dumas digestion method. The process involves the combustion of the plant material at 1250 °C in pure oxygen to produce N_2 and NO_x gases. These gases are then dehydrated and the No_x components reduced to N_2 in the presence of a copper catalyst. Carbon dioxide and any remaining water vapour are then removed and the N_2 gas, in a helium carrier gas passes over a conductivity cell measuring the amount of N present. The method produces a percentage of N present in the dried plant material.

2.3 STATISTICAL ANALYSIS

Data sets were analyzed by analysis of variance and regression, and curves were fitted using Genstat 5 Release 3. The treatment structure laid out in the tables is based upon the amount of basal N applied and then subdivided by the late-N treatments applied by timing of application, amount of N applied and the addition of an adjuvant.

The significant differences between means calculated by analysis of variance, have been indicated by the use of a *t*-test. Using this method the difference between two means was divided by the standard error of difference between means (SED) and the value produced compared with that published in *t* probability tables, for a given value of *P*. Where lines or curves have been fitted to data points, the equation producing the best fit for the given data set has been used, determined using the r^2 value.

Chapter 3: RESULTS OF THE FIELD EXPERIMENT AT IACR-ROTHAMSTED 1994

This experiment compared the effects of the timing of late-N application on the prolongation of GAI and the yields obtained from crops grown to a GAI of 5, contrasted with several differently sized canopies produced by varying the amount of basal N fertilizer applied. These basal N treatments were N0 - no N fertilizer applied, two crops grown to specific canopy size using the strategy of canopy management (GAI 3 and GAI 5), and a conventionally fertilized crop (Ncf).

3.1. EXPERIMENTAL DESIGN AND TREATMENTS APPLIED

The experiment was fully randomized and multifactorial, arranged in three randomised blocks, comprising the four basal-N treatments, two contrasting sowing dates, early (24 September 1993) and late (19 October 1993), and four late-N treatments. This resulted in a total of 16 separate treatments. The previous crop on the site of the experiment was winter oats which had received only 60 kg N ha^{-1} to ensure that the soil had a low N residue. The crop husbandry methods used in the experiment are detailed in Appendix 1.

3.1.1 **Basal-N applied**

The amount of N applied to produce crops with canopies of GAI 3 and GAI 5 was determined with regard to the rules and methods outlined in section 1.1.2, with values of 25 and 31 kg N ha^{-1} present in the soil on which the early and late sown crops respectively were growing when measured in February. It was calculated that an additional 200 kg N ha^{-1} was required to produce a crop with a canopy of GAI 5 and 100 kg N ha^{-1} for a canopy of GAI 3. N was applied to the crops as calcium nitrate $Ca(NO_3)_2$ (27 % N), as a split dressing of 60 kg N ha^{-1} to the GAI 5 and Ncf crops and 30 kg N ha^{-1} to the GAI 3 crop on 6 April 1994, with the balance applied on 28 April 1994. The amount of N applied to the Ncf crop, 265 kg N ha^{-1} was determined using the N present in the soil in

February, the estimated offtake of N in the crop and adjusted for an approximate expected grain yield of 7.5 t ha^{-1}.

3.1.2 Late-N treatments

The effect of timing of foliar urea application was tested on the GAI 5 crops. Applications were made at flag leaf emergence (GS 39) 24 May 1994, just prior to ear emergence (GS 51) 8 June and during anthesis (GS 65) 23 June. For the purposes of comparison late-N was also applied to the soil, 40 kg N ha^{-1} as solid calcium nitrate was applied evenly over the soil surface by hand, to a GAI 5 crop just prior to ear emergence (GS 51) on 8 June.

Foliar urea treatments were applied at a rate of 40 kg N ha^{-1} in 450 l water ha^{-1} using a Fox pressurised knapsack sprayer. This used a 3 m boom fitted with Lurmark 03-F110 110° flat fan nozzles (red) which gave a medium quality spray at an operating pressure of 2.5 bar with an output of 0.6 l min^{-1}, applied at 1 m s^{-1} (3.6 km h^{-1}). The urea was applied as two passes of 20 kg N ha^{-1} in 225 l water ha^{-1}.

Inclement weather and the lack of suitable spraying conditions meant that essential herbicide applications were not applied at the optimal times. As a result there was a large weed infestation especially in the third block of the experiment, that competed for N and light resulting in smaller canopies and lower yields than would otherwise have been expected. For this reason, the third block was omitted from subsequent statistical analysis to improve the precision of treatment comparisons. An initial statistical analysis showed that the values for the N0 treatment were extremely small relative to the other treatments, so the analysis was repeated excluding this treatment. Care was taken, in both cases, to ensure that sufficient residual degrees of freedom remained for comparison. Only when the treatment means were altered by the reanalyses are they quoted in the text.

3.2 CANOPY GROWTH AND PROLONGATION OF GREEN AREA

3.2.1 Canopy green area index

Figures 3.1 (a and b) and 3.2 (a and b) show the expansion in GAI of the early and late sown crops respectively during the growing season. In this experiment the GAIs of the crops were extremely small, much smaller than had been intended from the basal N fertilizer applied and that would be expected from conventional applications, GAIs of 7 and 8 are quite common. The GAI of the early sown crop was also smaller than that of the late sown one. The N0 crop produced a maximum GAI of 0.6, the crops fertilized to produce a GAI of 3 had a GAI of 1.6 when sown early and 2.3 when sown late. Both the Ncf and GAI 5 crops produced a maximum GAI of 3.5.

Measurements made on 21 March 1994, before N fertilizer was applied, showed that the early sown crop had a significantly larger GAI than the late sown one, 0.108 compared to 0.067, (SED = 0.0139, 8 df, $P = 0.05$). The effect of sowing date had disappeared when the crops were sampled on 6 and 28 April, by which time all of the basal N fertilizer treatments had been applied. At this time there was also no effect on GAI of the different amounts of N applied. However at the stage of stem extension at the beginning of May the N0 and GAI 3 crops had significantly smaller canopies than the GAI 5 and Ncf crops, and the late sown crop had a larger GAI than the early sown one ($P = 0.001$). The difference due to sowing date persisted for the remainder of the season.

The leaf canopies generally reached their maximum size by ear emergence, at the beginning of June. The GAI of the N0 crop did not exceed 0.6 from either sowing and remained significantly smaller than the other crops throughout growth. The GAI 3 crop achieved a maximum GAI of between 1.6 and 2.3 depending on sowing date which was significantly smaller than the GAI 5 and Ncf crops which were of similar size. The GAI 5 crop that received late-N as solid calcium nitrate at ear emergence produced a significantly larger canopy than the GAI 5 crop that did not receive late-N.

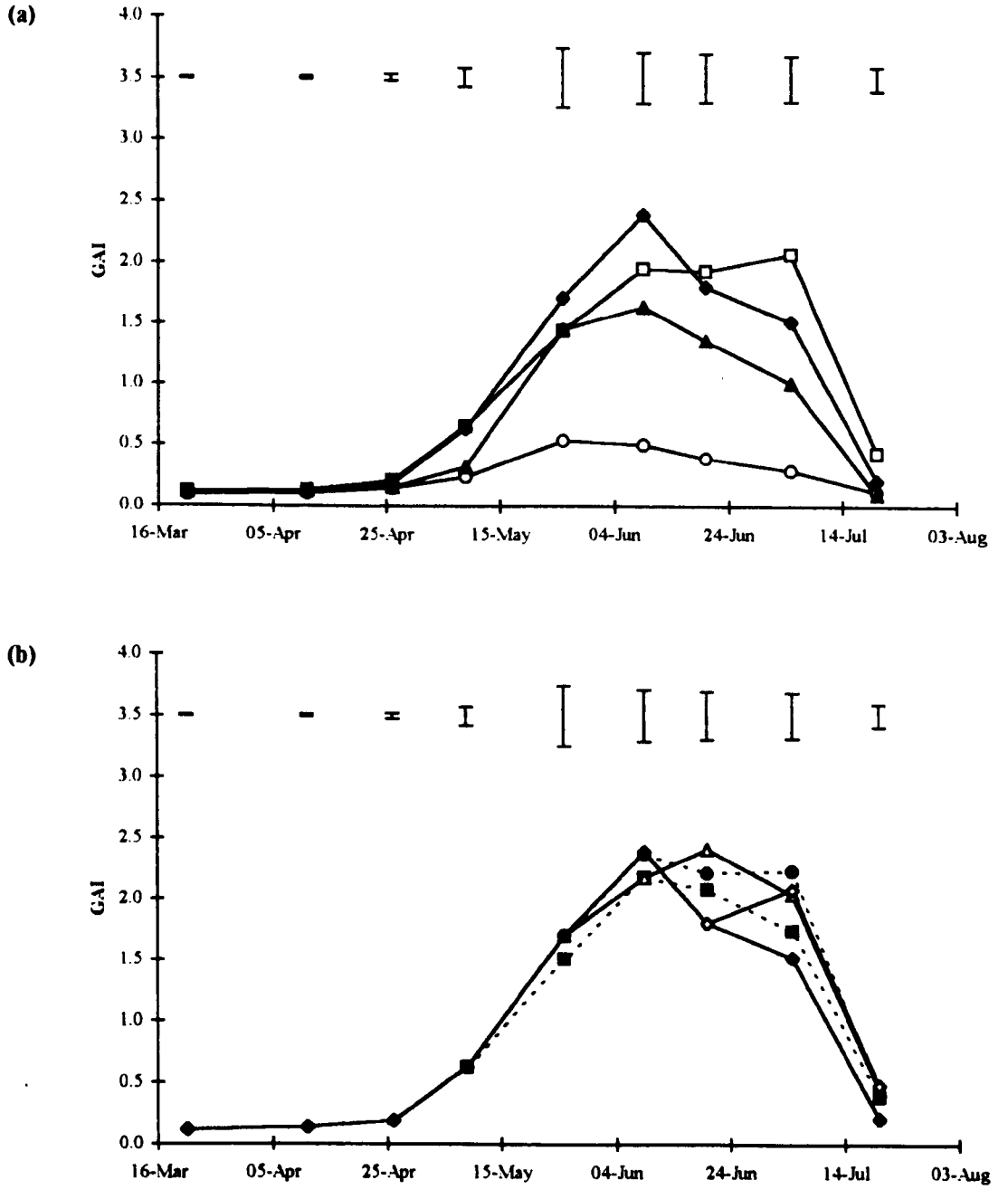


Figure 3.1 (a) the change in GAI of the four basal N crops over the whole of the growing season and (b) the effect of the application of late-N treatments either as foliar urea or soil applied calcium nitrate on the duration of GAI of the early sown crops at IACR-Rothamsted 1994. ○ N0 crop, □ Ncf crop, ▲ GAI 3 crop, ◆ GAI 5 crop, ■ GAI 5 + 40 kg N ha^{-1} as foliar urea at flag leaf emergence, △ GAI 5 + 40 kg N ha^{-1} as foliar urea at ear emergence, ● GAI 5 + 40 kg N ha^{-1} as solid calcium nitrate at ear emergence and ◊ GAI 5 + 40 kg N ha^{-1} as foliar urea at anthesis. The SEDs shown have 30 df.

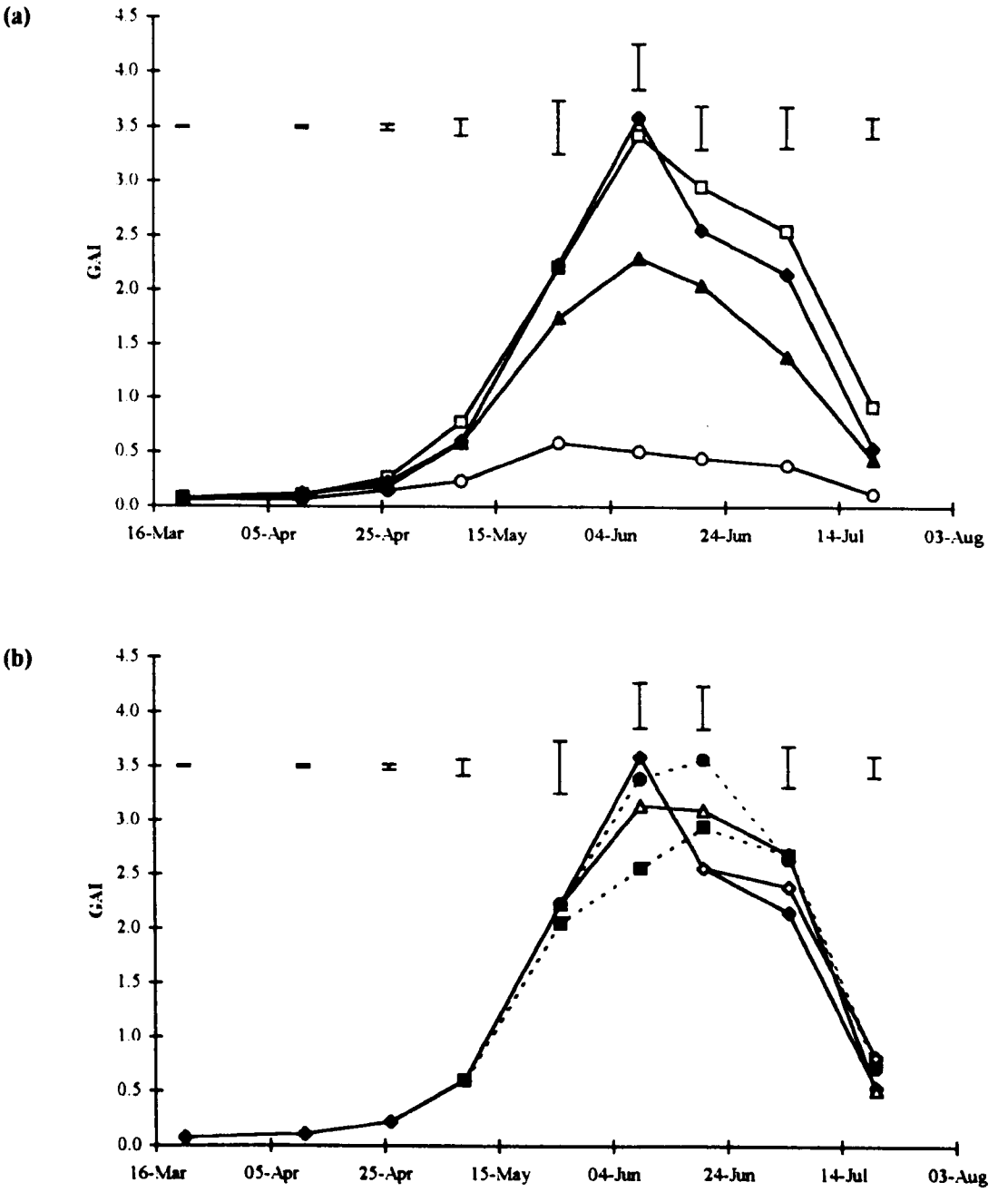


Figure 3.2 (a) the change in GAI of the four basal N crops over the whole of the growing season and (b) the effect of the application of late-N treatments either as foliar urea or soil applied calcium nitrate on the duration of GAI of the late sown crops at IACR-Rothamsted 1994. ○ N0 crop, □ Ncf crop, ▲ GAI 3 crop, ◆ GAI 5 crop, ■ GAI 5 + 40 kg N ha^{-1} as foliar urea at flag leaf emergence, △ GAI 5 + 40 kg N ha^{-1} as foliar urea at ear emergence, ● GAI 5 + 40 kg N ha^{-1} as solid calcium nitrate at ear emergence and ◊ GAI 5 + 40 kg N ha^{-1} as foliar urea at anthesis. The SEDs shown have 30 df.

The GAI of the canopies remained maximal until the end of June. After anthesis, GAI declined slowly between the end of June and mid-July and rapidly thereafter, especially in the GAI 3 crop and the GAI 5 crop that had not received late-N. The effects of the late-N became very apparent at this stage. Late-N slowed the senescence of the canopy and loss of green area irrespective of the time or method of application. The last measurement of GAI at the end of July showed that the green area of the GAI 5 crops that had received late-N were significantly larger than that of the GAI 5 crop given no late-N and similar in size to the Ncf crop.

All applications of late-N resulted in the prolongation of green area of the canopy in the GAI 5 crops, so that size remained similar to that of the Ncf crop. The late-N applied as foliar urea at anthesis appeared most effective at prolonging GAI during the final stages of growth whereas that applied at ear emergence, either as foliar urea or solid calcium nitrate, was more effective between anthesis and mid-July. These latter treatments may simply have become exhausted towards the end of the season, especially in the early sown crop.

3.2.2 Crop growth

Figures 3.3 (a and b) show the change in shoot number during the growing season for the early and late sown crops respectively. Shoot numbers m^{-2} initially increased as the wheat plants tillered at the beginning of the season and then decreased as tillers subsequently died, the numbers becoming constant by ear emergence. The application of basal N fertilizer increased shoot number m^{-2}.

Shoot numbers in the early sown crop were very low, only 250 m^{-2} were counted whereas numbers in excess of 400 are usually expected from this variety and site. The numbers progressively declined in the N0 crop until mid-May when they stabilised at around 150 m^{-2}, in other crops they remained relatively stable throughout growth. In the late sown crop, shoot numbers in the N0 crop also decreased during early growth, from about 200 to 150 m^{-2} by 26 May, but those in the other crops remained relatively constant. The late applications of N did not affect the number of

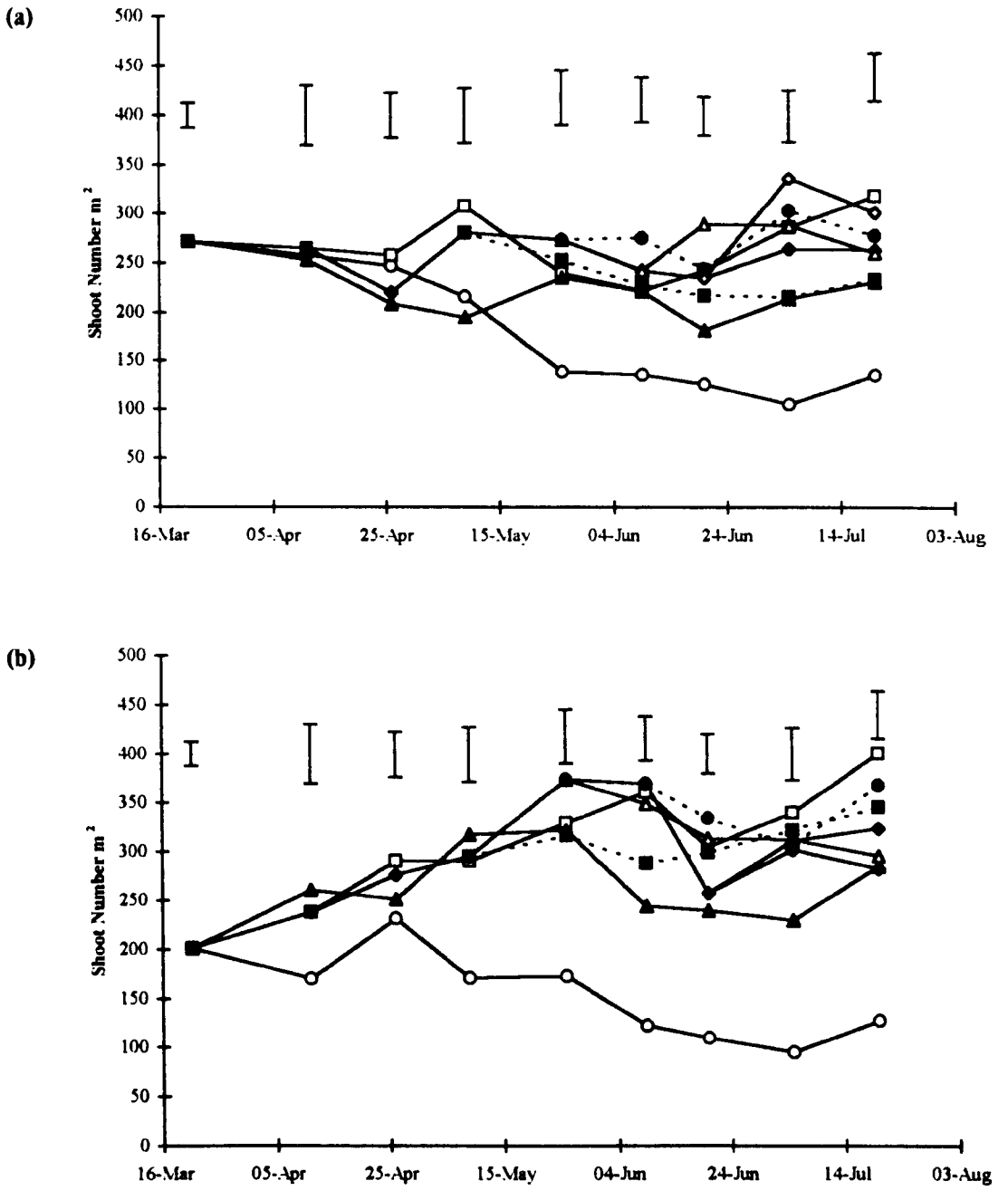


Figure 3.3 The change in shoot number m^{-2} of the four basal N crops over the whole of the growing season and the effect of the application of late-N treatments on shoot number for the early (a) and late (b) sown crops respectively at IACR-Rothamsted 1994. ○ N0 crop, □ Ncf crop, ▲ GAI 3 crop, ◆ GAI 5 crop, ■ GAI 5 + 40 kg N ha^{-1} as foliar urea at flag leaf emergence, △ GAI 5 + 40 kg N ha^{-1} as foliar urea at ear emergence, ● GAI 5 + 40 kg N ha^{-1} as solid calcium nitrate at ear emergence and ◊ GAI 5 + 40 kg N ha^{-1} as foliar urea at anthesis. The SEDs shown have 30 df.

shoots in either sowing. There were significantly more shoots in the late sown crop ($P = 0.001$), probably because this sowing was better established than the early sown one and did not suffer from such a large weed infestation.

Figures 3.4 (a and b) show the increase in crop biomass for the early and late sown crops respectively. Biomass accumulation in the fertilized crops followed the normal sigmoidal pattern observed in the most crops. The growth rates of both the early and late sown N0 crops remained slow and almost constant throughout growth, they struggled to achieve a total biomass of 2 t ha^{-1} by harvest. Although the early sown crops initially grew faster than the late sown ones, biomass yields were similar in the two by the end of May and greater in the late sown crop at harvest, (13 compared with 11 t ha^{-1}). The most apparent feature was that the total biomass of the GAI 3 crop was consistently lower than the GAI 5 and Ncf crops ($P = 0.001$). The application of late-N to a GAI 5 crop either as foliar urea or as solid calcium nitrate did not significantly affect crop biomass.

3.2.3 N uptake

The amount of N taken up by the crops was measured fortnightly during growth, uptake increased as the season progressed, figure 3.5 (a and b). The early and late sown N0 crops took up very little N during growth, both contained less than 25 kg N ha^{-1} at harvest. In the remaining basally fertilized crops, slightly more N was present in the late sown crop than the early sown ones, especially at ear emergence, by which time all crops had taken up much of the N present at harvest. The GAI 3 crop accumulated much less N (50 - 60 kg N ha^{-1}) than the GAI 5 and Ncf crops which contained similar amounts (100 - 120 kg N ha^{-1}). The late-N applications to the GAI 5 crops, especially those applied to the late sown crop, increased crop N content by about 20 - 30 kg N ha^{-1} irrespective of when or how they were applied.

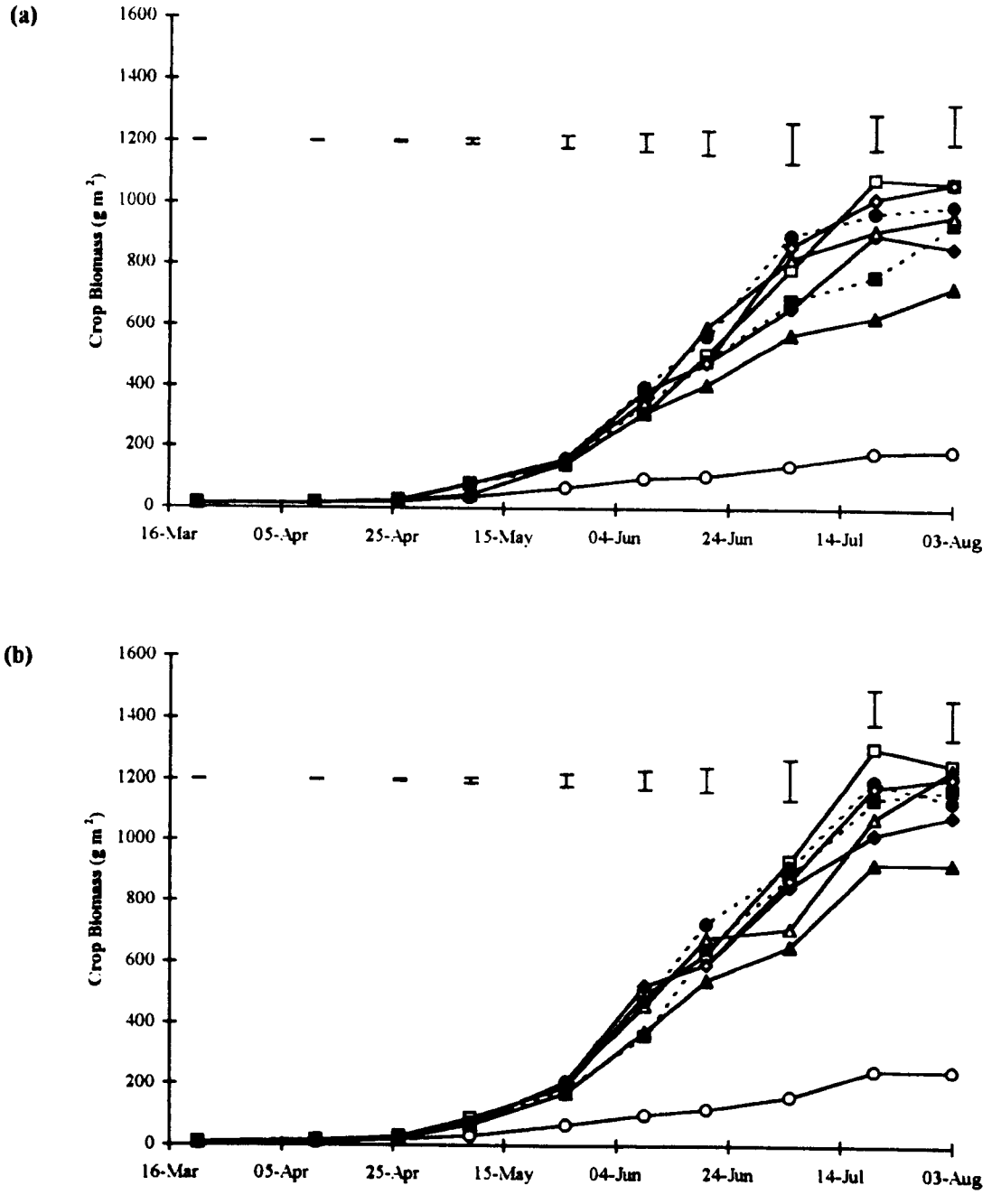


Figure 3.4 the change in crop biomass (g m^{-2}) of the four basal N crops over the whole of the growing season and the effect of the application of late-N treatments for the early (a) and late (b) sown crops respectively at IACR-Rothamsted in 1994. ○ N0 crop, □ Ncf crop, ▲ GAI 3 crop, ◆ GAI 5 crop, ■ GAI 5 + 40 kg N ha^{-1} as foliar urea at flag leaf emergence, △ GAI 5 + 40 kg N ha^{-1} as foliar urea at ear emergence, ● GAI 5 + 40 kg N ha^{-1} as solid calcium nitrate at ear emergence and ◊ GAI 5 + 40 kg N ha^{-1} as foliar urea at anthesis. The SEDs shown have 30 df.

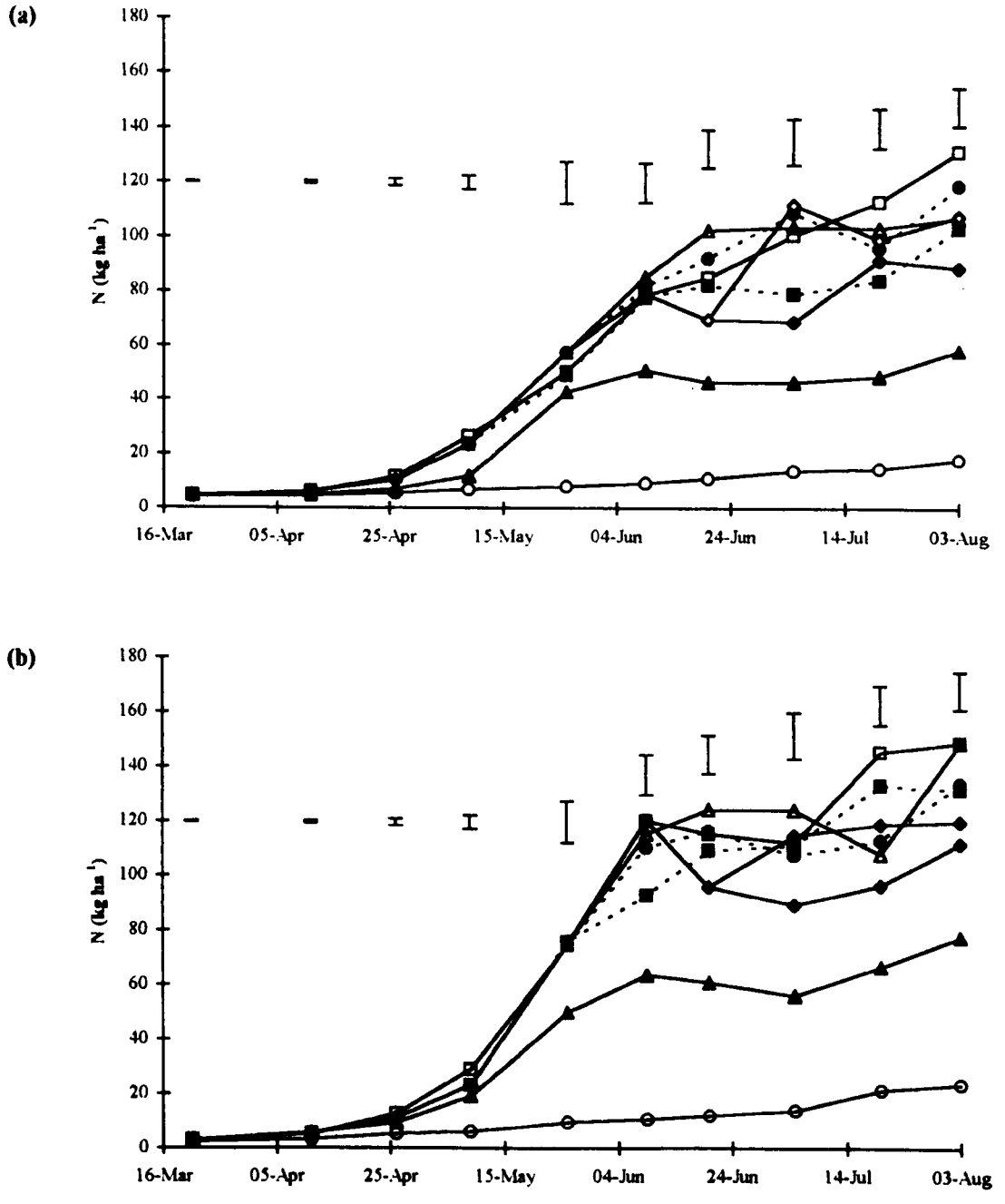


Figure 3.5 the N uptake (kg ha^{-1}) by the four basal N crops over the whole of the growing season and the effect of the application of late-N treatments for the early (a) and late (b) sown crops respectively at IACR-Rothamsted 1994. ○ N0 crop, □ Ncf crop, ▲ GAI 3 crop, ◆ GAI 5 crop, ■ GAI 5 + 40 kg N ha^{-1} as foliar urea at flag leaf emergence, Δ GAI 5 + 40 kg N ha^{-1} as foliar urea at ear emergence, ● GAI 5 + 40 kg N ha^{-1} as solid calcium nitrate at ear emergence and ◊ GAI 5 + 40 kg N ha^{-1} as foliar urea at anthesis. The SEDs shown have 30 df.

3.2.4 Weed problems

This experiment suffered a large weed infestation which particularly affected the early sown crop. It was partially caused by the inability to apply herbicide at the appropriate time in the spring, because of the lack of suitable spraying days. The herbicide applied on 24 May 1994, suppressed but did not kill the weeds, preventing further growth. Ground cover of weeds, assessed visually, was over 50 % in some parts of the experiment, especially in the third block. The major species present were *Alopecurus myosuroides* (black grass), *Galium aparine* (cleavers) and *Avena fatua* (wild oats), with smaller numbers of *Anthemis cotula* (mayweed), *Stellaria media* (chick weed), *Viola arvensis* (field pansy) and *Cirsium arvense* (thistle). The biomass and total N content of the weeds measured on 20 June are shown in table 3.1. Weeds compete directly with the crop for light, N, other nutrients and water and the weeds had become better established in the early sown crop before the onset of cold weather slowed germination and growth. The third block had a significantly greater infestation of weeds than the other two blocks for both sowings.

On average two to four times the weight of weeds was present in the early sown crop as compared to the late sown one and the weeds contained proportionately more N, ($P = 0.001$). The weight of weeds increased in proportion to the amounts of N applied in the basal fertilizer treatments, the weights and amounts being significantly smaller in the N0 crop than in the GAI 5 and Ncf crops, which contained similar amounts.

At the time of sampling, only the late-N treatment of foliar urea applied at flag leaf emergence had had sufficient time for the crop to respond to its application in terms of biomass, however there may have been enough time for the application of foliar urea at ear emergence to also have had an effect, as significantly more N was present in the weeds present in this crop than in the GAI 5 crop that did not receive late-N. Late-N applied as solid calcium nitrate at ear emergence did not significantly affect either biomass or N content of the weeds and foliar urea may have been more readily available to the weeds than the soil applied N.

Table 3.1 Mean biomass (DM, g m^{-2}) and mean N content (kg ha^{-1}) of weeds present on 20 June in the experiment at IACR-Rothamsted, 1994.

Treatment	Early Sown Crop		Late Sown Crop	
	Biomass	**N Content**	**Biomass**	**N Content**
N0 - no late-N applied	34.3	4.1	14.7	2.2
GAI 3 - no late-N applied	240.9	39.3	51.5	9.0
GAI 5 - no late-N applied	219.5	45.7	106.1	27.5
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	273.3	71.7	78.2	22.6
GAI 5 + 40 kg N ha^{-1} at ear emergence	250.9	59.8	92.6	27.7
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	172.5	42.0	90.3	26.8
GAI 5 + 40 kg N ha^{-1} at anthesis	219.5	45.7	106.1	27.5
Ncf - no late-N applied	194.2	50.9	100.9	33.5
SED (26 df)	31.80	6.85	31.80	6.85

Although the weeds present in the early sown crop contained a significantly greater amount of N (kg ha^{-1}) than those in the late sown crop, ($P = 0.001$, SED = 3.663, 26 df), the actual percentage concentration N in dry matter was smaller (2.60 compared with 2.19 %, $P = 0.001$, SED = 0.088, 26 df). The weed biomass in the GAI 5 crops was in excess of 200 g m^{-2} containing more than 50 kg N ha^{-1} on the 20 June and the corresponding crop biomass was greater than 550 kg N ha^{-1} containing approximately 100 kg N ha^{-1}. This indicates that the weeds contained almost half of the amount of N that was present in the crop and were therefore in direct competition with the wheat for nutrients.

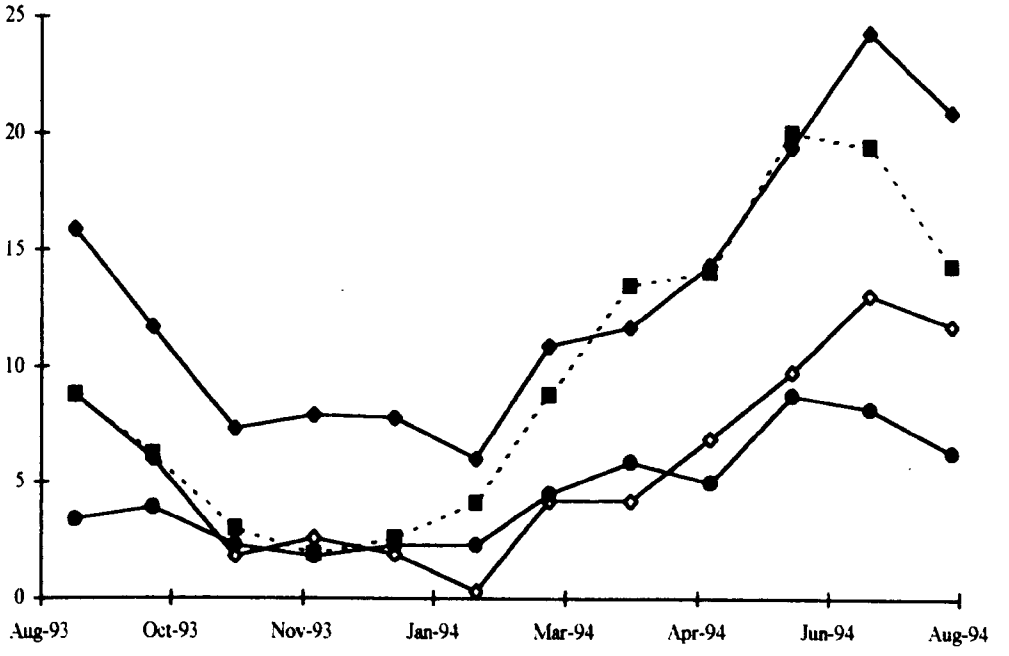
3.2.5 Weather Conditions

Figure 3.6 (a) shows the mean daily minimum and maximum temperature (°C), incident radiation (MJ m^{-2}) and hours of sunshine and Figure 3.6 (b) the total monthly rainfall (mm) and the wind speed (km h^{-1}) for the period 1 September 1993 to 31 August 1994. The data show that there was heavy rainfall in the spring which was partially responsible for the infestation of weeds and for the patchy nature of the late sown crops. There were no excessively droughted periods or extremes of temperature that may have greatly affected growth in the spring and early summer.

3.3 YIELD

Small areas within each plot were harvested by hand on 3 August to measure the components of yield and the plots were combined on 16 August. The yields are given in Tables 3.2 and 3.3 for the early and late sown crops respectively. The yields of grain obtained by the two harvest methods agreed reasonably well, but straw yields from the combine were, on average, only half those obtained by harvesting by hand. The late sown crop produced more grain, chaff and straw than the early sown ones ($P = 0.001$). The N0 crops produced the smallest grain yields (*c.* 0.9-1.5 t ha^{-1}) and the Ncf and GAI 5 crops that received late-N the largest (*c.* 5.5-5.9 t ha^{-1}), the GAI 3 crop yielded a significantly smaller amount of grain than the GAI 5 and Ncf crops. The yields of grain and straw from the GAI 5 crops were not significantly increased

(a)



(b)

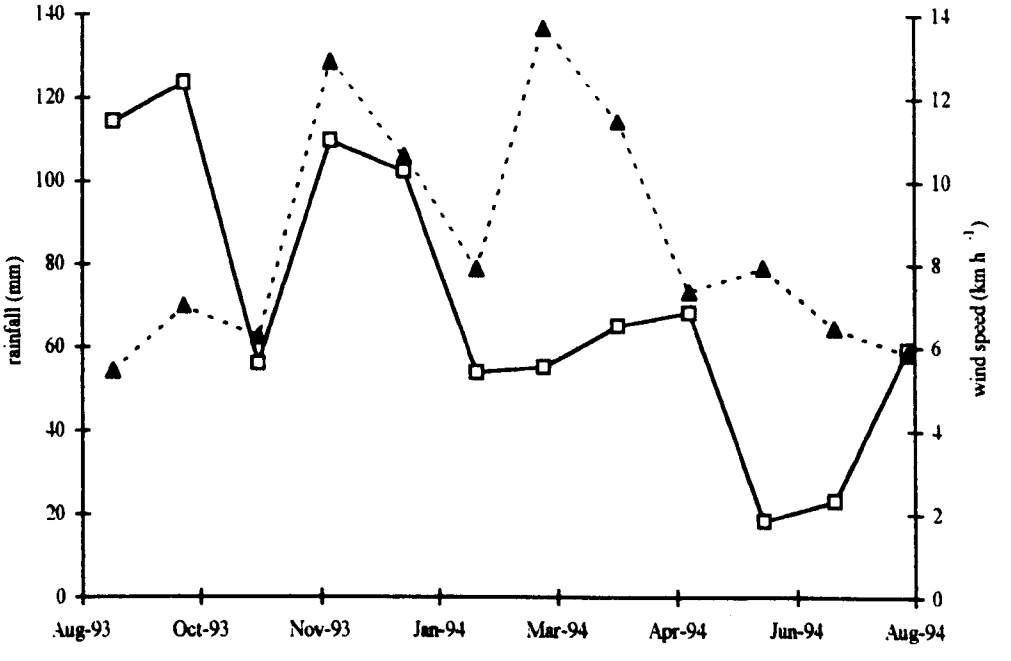


Figure 3.6 (a) mean daily minimum (◊) and maximum temperature, °C (◆), hours of sunshine (●) and incident radiation, MJ m^{-2} (■) and 3.6 (b) total monthly rainfall, mm (□) and wind speed, km h^{-1} (▲) for the period 1 September 1993 to 31 August 1994 at IACR-Rothamsted.

Table 3.2 Hand harvest components of yield (t ha^{-1}), 100 % DM, combine harvest yields (t ha^{-1}), 85 % DM and percentage harvest indices of the early sown wheat crop at IACR-Rothamsted 1994.

Treatment	Hand Harvest			Combine		% Harvest Indices		
	Grain	Chaff	Straw	Grain	Straw	Grain	Chaff	Straw
N0 - no late-N applied	0.94	0.27	1.3	0.93	0.18	51.8	13.8	34.5
GAI 3 - no late-N applied	3.25	0.75	5.3	3.63	2.46	50.9	10.3	38.7
GAI 5 - no late-N applied	4.23	1.11	5.5	5.43	3.41	51.5	12.9	35.6
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	4.43	1.08	6.6	5.44	2.99	53.1	11.3	35.5
GAI 5 + 40 kg N ha^{-1} at ear emergence	4.67	1.05	6.5	5.07	3.09	53.8	10.8	35.4
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	4.83	1.09	6.6	5.70	3.34	52.3	10.8	36.9
GAI 5 + 40 kg N ha^{-1} at anthesis	5.16	1.21	7.2	5.55	3.01	52.8	11.2	36.1
Ncf - no late-N applied	5.13	1.26	7.0	6.10	3.73	49.6	13.1	37.4
SED (30 df)	0.334	0.127	0.82	0.283	0.169	1.355	0.709	0.994

Table 3.3 Hand harvest components of yield (t ha^{-1}), 100 % DM, combine harvest yields (t ha^{-1}), 85 % DM and percentage harvest indices of the late sown wheat crop at IACR-Rothamsted 1994.

Treatment	Hand Harvest			Combine		% Harvest Indices		
	Grain	Chaff	Straw	Grain	Straw	Grain	Chaff	Straw
N0 - no late-N applied	1.21	0.31	1.8	1.70	0.59	53.6	12.6	33.8
GAI 3 - no late-N applied	4.36	1.08	6.9	4.76	2.85	51.2	11.6	37.2
GAI 5 - no late-N applied	5.01	1.38	7.7	6.43	3.95	49.5	12.6	38.0
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	5.26	1.40	8.2	6.68	4.30	50.3	12.0	37.8
GAI 5 + 40 kg N ha^{-1} at ear emergence	5.91	1.38	8.5	6.71	3.91	51.9	11.1	37.0
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	5.26	1.31	7.7	6.95	3.83	51.8	11.3	36.7
GAI 5 + 40 kg N ha^{-1} at anthesis	5.53	1.39	8.5	6.86	3.82	51.9	11.6	36.8
Ncf - no late-N applied	5.90	1.39	8.9	7.27	4.61	51.2	11.2	37.7
SED (30 df)	0.334	0.127	0.82	0.283	0.169	1.355	0.709	0.994

by the application of late-N at flag leaf emergence. However, both were increased by applications at anthesis and grain yields were increased by applications at ear emergence but only when the third replicate was removed from the statistical analysis.

The harvest indices (HI), the ratio of grain to the total crop biomass, expressed as a percentage, are given in Tables 3.2 and 3.3 for the early and late sown crop respectively. They are normally expected to be in the range of 50 % to 55 % for the grain, and 10-15 and 30-40 % respectively for chaff and straw (D.T. Stokes, personal communication). The values obtained were within these ranges. There was no significant affect of either sowing date or the basal or late-N fertilizer treatments on the grain percentage HI. The proportions of chaff and straw were not affected by sowing date, but the N0 crops generally had smaller harvest indices for straw and larger indices for chaff than crops receiving the other basal N treatments.

3.4 GRAIN QUALITY

Grain quality was measured by assessing the proportions of grain in different size fractions, measuring thousand grain weight, specific weight and Hagberg falling number. The data are shown in Tables 3.4 and 3.5 for the early and late sown crops respectively.

3.4.1 **Thousand grain weight**

Thousand grain weight (TGW) measured in grammes is a measure of mean grain size occasionally used to assess milling quality, as small light grains do not yield much flour. Although thousand grain weights were smaller in the late sown than the early sown crop the differences were not statistically significant. Thousand grain weights were smaller in the N0 crop than in crops that had received N fertilizer and larger in the GAI 5 crops to which late-N had been applied as foliar urea or solid calcium nitrate at ear emergence and as foliar urea at anthesis ($P = 0.001$).

Table 3.4 The percentage and yield (t ha^{-1}) of grain falling within specific size fractions (mm), the specific grain weight, kg hl^{-1} (SGW), thousand grain weight, g (TGW), Hagberg falling number (HFN) and percentage N content of combine harvested grain at 85 % DM, of the early sown crop at IACR-Rothamsted in 1994.

Treatment	1-3.5	Yield	1-2.2	Yield	2.2-3.5	Yield	SGW	TGW	HFN	% N
N0 - no late-N applied	96.0	0.89	12.1	0.111	83.91	0.778	77.2	35.6	299.0	1.573
GAI 3 - no late-N applied	98.0	3.56	9.07	0.328	88.92	3.229	77.6	39.2	303.0	1.380
GAI 5 - no late-N applied	98.3	5.33	7.51	0.408	90.76	4.927	78.1	40.0	331.3	1.640
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	98.3	5.35	8.00	0.431	90.34	4.917	78.2	39.9	318.3	1.804
GAI 5 + 40 kg N ha^{-1} at ear emergence	98.2	4.98	7.34	0.371	90.90	4.611	78.5	41.1	323.3	1.774
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	98.2	5.60	6.89	0.385	91.30	5.211	78.9	41.5	326.7	1.784
GAI 5 + 40 kg N ha^{-1} at anthesis	98.3	5.46	7.33	0.409	90.99	5.046	79.2	41.4	323.0	1.792
Ncf - no late-N applied	98.4	6.00	6.75	0.414	91.65	5.586	79.1	40.5	326.7	1.896
SED (30 df)	0.111	0.278	0.480	0.030	0.548	0.257	0.240	0.50	4.58	0.0479

Table 3.5 The percentage and yield (t ha^{-1}) of grain falling within specific size fractions (mm), the specific grain weight, kg hl^{-1} (SGW), thousand grain weight, g (TGW), Hagberg falling number (HFN) and percentage N content of combine harvested grain at 85 % DM, of the late sown crop at IACR-Rothamsted in 1994.

Treatment	1-3.5	Yield	1-2.2	Yield	2.2-3.5	Yield	SGW	TGW	HFN	% N
N0 - no late-N applied	97.6	1.66	10.0	0.172	87.61	1.490	76.7	38.7	306.0	1.484
GAI 3 - no late-N applied	98.2	4.71	8.51	0.407	89.86	4.299	76.0	39.4	304.0	1.351
GAI 5 - no late-N applied	98.3	6.29	7.32	0.468	90.96	5.819	78.3	39.3	335.5	1.737
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	98.6	6.59	7.31	0.488	91.28	6.101	79.0	39.9	336.0	1.895
GAI 5 + 40 kg N ha^{-1} at ear emergence	98.4	6.61	6.47	0.436	91.94	6.172	79.0	39.2	329.7	1.878
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	98.4	6.84	6.57	0.457	91.78	6.378	79.1	40.7	329.0	1.801
GAI 5 + 40 kg N ha^{-1} at anthesis	98.3	6.75	6.43	0.438	91.96	6.309	78.6	41.2	312.0	1.797
Ncf - no late-N applied	98.4	7.15	6.43	0.470	91.96	6.680	79.7	39.4	331.3	2.095
SED (30 df)	0.111	0.278	0.480	0.030	0.548	0.257	0.240	0.50	4.58	0.0479

3.4.2 Specific grain weight

Specific grain weight (SGW) or hectolitre weight is a measure of the bulk density of the grain and an indicator of good milling quality. Values above 76 kg hl^{-1} indicate well filled, plump grains from which more flour can be extracted. Specific grain weights were not affected by sowing date but were increased by the application of basal N fertilizer (the Ncf crop producing the largest grains) and by the applications of late-N as foliar urea to GAI 5 crops at ear emergence and anthesis.

3.4.3 Grain size

A greater proportion of the grain from the late sown crops occurred in the size range 2.2-3.5 mm and less in the 1-2.2 mm range than in the early sown crops. More small grain, less than 2.2 mm in size, was present in the grain from the N0 and the GAI 3 crops than in grain from the GAI 5 and Ncf crops, ($P = 0.001$). The proportion of grain within the different size categories was not affected by any of the late-N treatments applied to the GAI 5 crops.

3.4.4 Hagberg falling number

Hagberg falling number (HFN) is an indirect measure of alpha amylase activity in the grain. Values, below 150 indicate high enzyme activity which results in a sticky crumb structure, values above 350 indicate low enzyme activity that produces dry and dense loaves, HFNs between 250 - 350 produce a good, acceptable crumb structure.

Sowing date did not significantly affect HFNs, but grain from the N0 and the GAI 3 crops had significantly smaller HFNs than the other treatments ($P = 0.001$) and values for the GAI 5 and Ncf crops were similar. Foliar urea applied to the early sown GAI 5 crop at flag leaf emergence or to the late sown GAI 5 crop at anthesis produced grain with significantly lower HFNs than crops which did not receive late-N. Overall, the grain from all the treatments fell within the desired HFN range.

3.4.5 Grain N percentage

The percentage N content of the early sown crop was significantly lower than that of the late sown crop (1.705 compared with 1.755, SED = 0.0169, 30 df, $P = 0.01$). The application of basal N fertilizer resulted in a significant increase in percentage N content of the grain with the exception of the GAI 3 crop which contained a significantly smaller percentage of N than the N0 crop in both the early and the late sown crops ($P = 0.01$). The application of late-N to the GAI 5 crops resulted in a significant increase in percent N content compared to when late-N was not applied ($P = 0.01$), however there were no significant differences in the effectiveness of the different late-N treatments and all were significantly lower than the amount present in the Ncf crop.

Using a conversion factor of 5.7 to determine the amount of protein present in the grain only the late sown Ncf crop would have exceeded 11 % protein content.

3.5 N PRESENT IN THE CROP AT HARVEST

3.5.1 N uptake and harvest index

The total amounts of N present in the different parts of the hand harvested crop are shown in Table 3.6. The percentage harvest index for N recovered in the grain (N HI), is the grain N content expressed as a percentage of the N recovered in the total biomass.

Table 3.6 N present in the hand harvested crop (kg ha^{-1}), total uptake (kg ha^{-1}) and the percentage N harvest index of the grain at IACR-Rothamsted in 1994.

	Early Sown Crop					Late Sown Crop				
Treatment	**Grain**	**Chaff**	**Straw**	**Total**	**N HI**	**Grain**	**Chaff**	**Straw**	**Total**	**N HI**
N0 - no late-N applied	14.05	1.48	2.61	18.15	78.0	18.40	1.48	3.48	23.36	78.8
GAI 3 - no late-N applied	44.54	2.83	11.10	58.46	76.2	60.39	4.52	12.37	77.27	78.2
GAI 5 - no late-N applied	70.73	5.66	12.41	88.80	79.7	87.14	6.93	17.73	111.8	77.9
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	82.32	4.82	16.31	103.4	79.6	102.0	7.76	21.87	131.7	77.4
GAI 5 + 40 kg N ha^{-1} at ear emergence	85.52	5.08	16.42	107.0	79.9	117.7	7.30	23.78	148.8	79.1
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	85.44	4.95	17.44	107.8	79.2	95.90	5.98	18.10	120.0	79.9
GAI 5 + 40 kg N ha^{-1} at anthesis	94.93	5.41	18.56	118.8	79.9	106.0	6.53	21.39	133.9	79.2
Ncf - no late-N applied	103.4	6.47	21.66	131.6	78.6	116.3	7.38	25.08	148.8	78.2
SED (30 df)	7.356	0.627	2.436	9.850	1.001	7.356	0.627	2.436	9.850	1.001

On average, each part of the late sown crops contained significantly more N at harvest than the early sown crops (72.63 compared with 88.01 kg N ha^{-1}, SED = 3.678 in the grain, 4.59 compared with 5.99 kg N ha^{-1}, SED = 0.313 in the chaff and 14.56 compared with 17.97, SED = 1.218 in straw, 30 df, $P = 0.01$), the amounts in the N0, GAI 3 and GAI 5 crops were also smaller than in the Ncf crop ($P = 0.001$). The late sown GAI 5 crops responded better, in terms of N uptake, than the early sown crops, to the late-N treatments. In the late sown crops, foliar urea applied at flag leaf emergence or at anthesis increased the amount of N in the grain, and that applied at anthesis also increased the N in the straw. The total N contents of these crops at harvest were similar to that of the Ncf crop. In the early sown crops, only foliar urea applied at anthesis increased grain N. None of the late-N treatments affected the N content of the chaff.

The nitrogen harvest index was unaffected by sowing date or the amounts of N applied either as basal or late-N treatments. The measured N harvest index values were, however, greater than expected, normally the N HI for a conventionally fertilized crop would be approximately 70 %, that for a GAI 5 crop approximately 75 % and for an N0 crop 80 % (D.T.Stokes, personal communication).

3.5.2 **Percentage apparent N recovery**

The percentage apparent N recovered by the crops, estimating the amount of fertilizer N taken up and excluding any N present in the soil, is shown in Table 3.7. It is calculated as the total N uptake minus the amount of N taken up by the N0 crop divided by the total amount of N fertilizer applied. On average less than 50 % of the applied N fertilizer was taken up by the crops, the late sown crop recovered significantly more N than the early sown crop, (46.8 compared with 38.6 %, SED = 1.954, 16 df, $P = 0.01$). None of the basal or late-N treatments affected the percentage recovery of N.

Table 3.7 The apparent N recovery (%) calculated for the early and late sown crops from the total amount of N applied (kg ha^{-1}), basal and late, and the total N uptake (kg ha^{-1}) at IACR-Rothamsted 1994.

Treatment	Early Sown Crop					Late Sown Crop				
	Basal	**Late**	**Total**	**Total Uptake**	**Apparent N Recovery**	**Basal**	**Late**	**Total**	**Total Uptake**	**Apparent N Recovery**
N0 - no late-N applied	0	0	0	18.1	-	0	0	0	23.4	-
GAI 3 - no late-N applied	100	0	100	58.4	40.3	100	0	100	77.3	52.9
GAI 5 - no late-N applied	200	0	200	88.8	35.3	200	0	200	111.8	44.2
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	200	40	240	103.4	35.5	200	40	240	131.7	45.2
GAI 5 + 40 kg N ha^{-1} at ear emergence	200	40	240	107.0	37.0	200	40	240	148.8	52.3
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	200	40	240	107.8	37.4	200	40	240	120.0	40.2
GAI 5 + 40 kg N ha^{-1} at anthesis	200	40	240	118.9	42.0	200	40	240	133.9	46.1
Ncf - no late-N applied	265	0	265	131.6	42.8	265	0	265	148.8	47.3
SED (30 df)	-	-	-	9.850	6.401	-	-	-	9.850	6.401

3.5.3 Recovery of late-N

Table 3.8 shows the percentage recovery and the amount (kg N ha^{-1}) of late-N recovered from applications made to GAI 5 crops. This was calculated as the difference in the total N content and the N content of the grain between the GAI 5 crop that did not receive late-N and the GAI 5 crops that did. There were no significant differences in the amount or the percentage of late-N recovered in either the grain or in the whole crop as the data were so variable. However the majority of the late-N was recovered in the grain, approximately 30 - 75 % with small additional amounts present in the rest of the plant. There appeared to be no effect of sowing date or the timing of late-N application upon the amount of late-N recovered.

Table 3.8 The amount (kg N ha^{-1}) and the percentage of late-N recovered in the grain and in the whole crop (in addition to that present in the GAI 5 crop that did not receive late-N) after application of late-N to GAI 5 crops, measured at harvest at IACR-Rothamsted, 1994.

Treatment	N Recovered in the grain (kg ha^{-1})	% N Recovered in the grain	Total N Recovered (kg ha^{-1})	% Total N Recovered
Early Sown				
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	11.6	28.9	14.6	36.5
GAI 5 + 40 kg N ha^{-1} at ear emergence	14.8	36.9	18.2	45.5
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	14.7	36.7	19.0	47.5
GAI 5 + 40 kg N ha^{-1} at anthesis	24.2	60.5	30.1	75.0
Late Sown				
GAI 5 + 40 kg N ha^{-1} at flag leaf emergence	14.9	37.4	19.9	49.8
GAI 5 + 40 kg N ha^{-1} at ear emergence	30.6	76.5	36.9	92.5
GAI 5 + 40 kg N ha^{-1} calcium nitrate at ear emergence	8.79	21.9	8.20	20.5
GAI 5 + 40 kg N ha^{-1} at anthesis	18.9	47.0	22.2	55.5
SED (16 df)	10.79	26.97	16.54	41.33

3.6 DISCUSSION AND CONCLUSIONS

The basal N fertilizer treatments produced canopies of contrasting size and N content. However, the weather conditions in spring resulted in very low residual amounts of soil mineral N through leaching losses and the large infestation of weeds resulting from the inability to apply herbicide at the appropriate time. This meant that the GAIs of the canopies and the final yields obtained were considerably smaller than might otherwise be expected from this variety and site.

3.6.1 **The effect of the weeds**

The weed biomass exceeded 2 t ha^{-1} in some of the treatments, notably the early sown GAI 3 and GAI 5 crops. Although herbicides were applied on 24 May, this was considerably later than the optimum time for control of blackgrass which is about the three leaf stage of development. The herbicides did not control the weeds adequately and may have had a deleterious effect on crop performance by temporarily reducing growth, compounding the effect of the weeds, especially as it has been reported that the presence of weeds reduce the ability of the crop to take up and use N (Grundy, Boatman and Froud-Williams, 1996). This ultimately affects grain quality and yield (Friesen, Shebeski and Robinson, 1960). However, it has been suggested that the composition of the weed species present also affects yield and N uptake (Gooding, Davies, Thompson and Smith, 1993), as some weeds have a greater competitive effect than others. In this experiment the predominant species were *Alopecurus myosuroides*, *Galium aparine* and *Avena fatua*. Cussans, J.W. (personal communication), found that *A. myosuroides* and *G. aparine* benefited greatly from applications of N fertilizer, out competing wheat for this resource and therefore ultimately reducing both total N uptake and yield by the wheat. This was confirmed by the relatively high N content of the weeds when measured on 20 June, 72 kg N ha^{-1} compared to 124 kg N ha^{-1} for the weeds and wheat respectively.

The early sown crops had a much greater weed biomass that contained more of the available N than the weed biomass present in the late sown crops. The early sown winter crop allowed the germination and establishment of weeds before the onset of colder weather. Later cultivations disturbed the weeds that had already germinated and become established and shortened the time for succesful establishment before winter. Early emergence of wheat has been found to suppress growth and nutrient uptake by the wild oat *Avena sterilis* (Ponce, 1987), but later emergence reduced this effect probably because the oats were able to out compete the wheat for water (Ponce and Senas, 1983). This has also been reported for other weed species, for example *Agropyron repens* and *A. myosuroides* (Welbank, 1961 and 1963). In this experiment, the late summer was dry and warm and less water was available which may have added to the smaller final yields obtained. The weeds will also have competed for incident radiation and therefore contributing to the reduction in dry matter accumulated by the crops.

3.6.2 **The prolongation of GAI**

The application of late-N to the GAI 5 crops either as foliar urea or solid calcium nitrate applied to the soil resulted in the prolongation of GAI; a greater proportion of the canopy was green on the last occasion on which GAI was measured compared to when late-N was not applied. Maximum GAI was reached on 6 June, at ear emergence, (as predicted by the rules for canopy management, section 1.1.2, Sylvester-Bradley 1993; Stokes *et al.*, 1997) by the GAI 5 crop which did not receive late-N, there was then a subsequent rapid decline in GAI. Crops given late-N attained a smaller maximum GAI, possibly due to some leaf scorch from the foliar applications, the peak was reached later in the season and the canopy size remained relatively stable for between two and four weeks before declining rapidly, caused by the warm, dry weather conditions at that time (mid to late July).

Foliar urea applied at flag leaf emergence to a GAI 5 crop succeeded in maintaining the duration of the green area after anthesis, when senescence had commenced. The application of calcium nitrate to the soil at ear emergence was the most effective in

maintaining green area, suggesting that this source of N was more readily available to the crop than that sourced from foliar applications. On this occasion the calcium nitrate was applied to damp soil, but this may not always be the case during the summer months. The application of foliar urea at ear emergence was not as affective as the corresponding soil application in maintaining GAI, probably because some of the N was intercepted by the weeds, but it did result in some prolongation of the GAI. Foliar urea applied at anthesis reduced the rate at which the GAI declined and in the early sown crop appeared to cause an increase in GAI. However, this may not have been a true effect, since at this stage of growth maximum GAI had already been reached and once green tissue has senesced it cannot be regenerated. This treatment had the largest GAI on the final sample date. Therefore the late-N treatments succeeded in maintaining GAI, by either replacing the N from the foliage that had been translocated to the grain or by supplying N directly to the grain, resulting in continued photosynthetic activity and dry matter production. Each of the late-N applications may have resulted in the N supplied being used in a different way by the crops. Earlier late-N applications, at full flag leaf emergence or prior to full ear emergence, may have been exhausted by anthesis resulting in reduced yields at final harvest and a more rapid decline in the green area. The anthesis application of late-N may not have benefited the weeds as much as those applied at flag leaf and ear emergence.

The application of late-N did not significantly affect shoot number which was already set by the time of the first application of foliar urea. Tiller death was also largely complete, with the exception of the N0 crop which showed a continual decline in shoot numbers as the N available for growth declined. Late-N applications did not have a significant impact on dry matter accumulation immediately after their application and any effects on dry matter did not become apparent until harvest.

3.6.3 **Grain yield and quality**

Generally, the late sown crops (sown on 19 October 1993) produced larger yields of grain than the early sown ones (24 September 1993). However, more of the total biomass was

partitioned to the grain than to the chaff and straw in the early than the late sown crops, perhaps in compensation for the reduced amounts of N available through the competitive effects of the weeds. This is confirmed by the N0 crops of both sowings which were grown in highly nutrient deficient conditions, where more biomass was partitioned to the grain and less to the chaff and straw.

The application of basal N fertilizer resulted in a significant increase in grain yield and grain N content, both increasing progressively with the amount of basal N applied. There were no significant differences in the grain yield obtained from the GAI 5 crops receiving late-N. However, given the large infestation of weeds in 1994, it is likely that the late applications of foliar urea and soil applied calcium nitrate replaced N that had been lost to the weeds earlier in the season and that the earlier late-N applications, were themselves subject to loss to the weeds.

The values for Hagberg falling number and specific grain weight were within the desired ranges and were similar to the values recorded by Dampney *et al.*, (1995), which studied the effects of foliar urea on the protein and bread making quality of grain. HFN and specific grain weight were not affected by sowing date, but basal N and late-N treatment did have some effect. Both were increased by increasing amounts of basal N and foliar urea applied at flag leaf emergence (early sown crop) and anthesis (late sown crop) had a detrimental effect on HFN compared to the value obtained for the GAI 5 crop that did not receive late-N. Thousand grain weight was increased by the basal N fertilizer treatments but not by any of the late-N treatments. This may be related to the relatively constant proportion of biomass that was partitioned to the grain, shown by values for the grain harvest index.

3.6.4 **N uptake**

Only the residual mineral N was present in the spring and that mineralized during growth was available to the N0 crop. It therefore contained significantly less N both during growth

and at harvest than the crops that received basal N fertilizer. The Ncf crop, as would be expected, contained at harvest and during growth more N than the other crops, however uptake was similar to that of the GAI 5 crops that received late foliar N. The application of solid calcium nitrate to the soil at ear emergence to a GAI 5 crop increased N content during growth and increased yield but did not significantly increase the N content of the grain, possibly because a proportion of the N was not transported to the ear.

The late-N applications of foliar urea to the GAI 5 crops increased grain yield and grain N content relative to that of the GAI 5 crop that did not receive late-N. In the early sown crops a significant difference was only shown by the application of foliar urea at ear emergence and in the late sown crops from the anthesis application. The different responses may be related to the relative development of the two sowings. The late sown crop which had a larger biomass and GAI than the early sown one, may have required more N to sustain dry matter accumulation at point earlier in the season, at ear emergence, than the early sown crop, which did not require the N until a later developmental stage. As the early sown crop was smaller it may not have reached the optimum time for late-N application until anthesis, *i.e.* when the late-N was of most benefit to the crop. N may have been a limiting factor before these late-N applications. Therefore the extra late-N from either foliar or soil applications was taken up by the crop and appeared in the grain. Between 20 and 30 kg N ha^{-1} extra was present in total in the whole crop, the majority of which was partitioned to the grain. As the data were so variable, there were no significant differences in the amount of N recovered by the GAI 5 crops either in the grain or in total from the late-N applications. However, the data do indicate that the late-N was taken up by the crop and a major proportion of this (between 40 and 75 %) was partitioned to the grain by final harvest, resulting in an increase in the % N content of the grain.

On the basis of the protein content of the grain, (calculated as % N multiplied by 5.7) only the GAI 5 crops receiving late-N and the Ncf crops would have reached the market threshold for bread making quality of 11 % protein. Therefore the extra late-N either as

foliar urea or soil applied calcium nitrate was important to sustain the potential for additional revenue.

The recovery of the available N differed between the sowing dates probably because of the large weed population present in the early sown crop. The late sown crop recovered significantly more of the available N, both that present in the soil and that applied as fertilizer, than the early sown crop.

In this experiment, the application of late-N to the GAI 5 crop had the beneficial effect of prolonging GAI and increasing yield, grain quality and N uptake. In most cases the performance of the GAI 5 crops given late-N did not differ significantly from the Ncf crop and the effects were the same irrespective of whether late-N was applied to the soil or to the foliage. Therefore in the field experiments carried out in 1995 at IACR-Rothamsted and Sutton Bonington, foliar urea applications were made to examine the effects of a range of treatments including timing of application, the size and N status of the canopy to which they were applied, the use of different types of adjuvant and the amount of N applied, on the prolongation of the canopy green area and grain yield.

Chapter 4: RESULTS OF THE FIELD EXPERIMENT AT IACR-ROTHAMSTED 1995

Three contrasting crops were grown to produce sufficient plant material on which to examine the most effective method of applying late-N as foliar urea.

4.1 EXPERIMENTAL DESIGN AND TREATMENTS APPLIED

The experiment was set up with the aim of analysing the effects of different factors associated with the application of foliar urea as a late-N application. The affects on the dynamics of N uptake, the prolongation of GAI and the yield of Canopy Managed (GAI 5) crops were examined. Different late-N treatments examining timing, amount of N applied and the use of adjuvants, were applied to GAI 5 crops and late-N was also applied to an N0 and an Ncf crop.

The experiment, sown on 21 September 1994 was arranged in three fully randomised blocks of the three basal-N treatments, N0, GAI 5 and Ncf. The basal N treatment plots were divided into five sub-plots, each receiving a different foliar late-N treatment, which were fully randomised within each block. The crop husbandry methods used in the experiment are shown in Appendix 1. The previous crop was winter oats which had received 100 kg N ha^{-1}.

The amount of basal N required by the GAI 5 crop was determined using the rules outlined in section 1.1.2. 24 kg N ha^{-1} was present in the soil and 16 kg N ha^{-1} in the crop in February and assuming that 150 kg N ha^{-1} would be required for the crop to produce a canopy of GAI 5, 120 kg N ha^{-1} was applied. The amount of N to be applied to the Ncf treatment was calculated using the amount of N present in the crop and the soil mineral N in February, previous cropping history, sowing date and expected yield and in accordance with ADAS recommendations, 200 kg N ha^{-1} was applied. Ammonium nitrate, (34.5 %

N), was applied as a split dressing of 30 kg N ha^{-1} on 16 March with the balance on 12 April.

4.1.1 Late-N treatments

Depending upon the factors being analyzed, the late-N foliar urea treatments were applied to the N0, Ncf and GAI 5 crops, but not necessarily in factorial combinations.

The factors that were examined were:

i) timing of application: 30 kg N ha^{-1} was applied at flag leaf emergence (GS 39), just prior to ear emergence (GS 51) and during anthesis (GS 61) to GAI 5 crops.

ii) size and N status of the canopy: 30 kg N ha^{-1} was applied at anthesis to N0, GAI 5 and Ncf crops.

iii) amount of N applied: 30 kg N ha^{-1} was compared with 60 kg N ha^{-1} at anthesis to GAI 5 crops.

iv) effect of adjuvants: 30 kg N ha^{-1} was applied to GAI 5 crops with a 0.1 % solution of an adjuvant, these were a spreader (Silwet L-77), a sticker (Spray-Fix) and a penetrant (LI-700), (Newman Agrochemicals, Cambridge) and applied just prior to ear emergence (GS 51). 30 kg N ha^{-1} with 0.1 % Silwet L-77 was also applied at anthesis to a GAI 5 crop.

Table 4.1 shows the treatments applied and the dates of application.

Foliar urea was applied using a CO_2 pressurised knapsack sprayer, with a 3 m spray boom fitted with Lurmark 03-F110 110° flat fan nozzles (red), producing a medium quality spray at 3.0 bar pressure, with an output of 0.542 l min^{-1} at 0.625 m s^{-1} (2.25 km h^{-1}). The boom was held 0.5 m above the crop surface.

Table 4.1 Late-N treatments as foliar urea applied to the field experiment at IACR-Rothamsted in 1995.

Basal-N Treatment	Foliar N Treatment	Timing of Application (GS)	Date
N0	none	-	-
N0	30 kg N ha^{-1}	anthesis (65)	13 June
GAI 5	none	-	-
GAI 5 [1]	30 kg N ha^{-1}	flag leaf emergence (39)	16 May
GAI 5	30 kg N ha^{-1}	ear emergence (51)	26 May
GAI 5	30 kg N ha^{-1} + 0.1 % Silwet L-77	ear emergence (55)	01 June
GAI 5	30 kg N ha^{-1} + 0.1 % Spray-Fix	ear emergence (55)	02 June
GAI 5	30 kg N ha^{-1} + 0.1 % LI-700	ear emergence (55)	02 June
GAI 5	30 kg N ha^{-1}	anthesis (61)	08 June
GAI 5	60 kg N ha^{-1}	anthesis (65)	14 June
GAI 5	30 kg N ha^{-1} + 0.1 % Silwet L-77	anthesis (68)	15 June
Ncf	none	-	-
Ncf[2]	30 kg N ha^{-1}	anthesis (65)	13 June

1 Treatment was not sampled for urea deposition

2 An additional 50 kg N ha^{-1} as prilled ammonium nitrate was applied by hand on 25 May 1995 to ensure that the Ncf crop was over supplied with N compared to a GAI 5 crop.

4.2 CANOPY GROWTH AND GREEN AREA PROLONGATION

4.2.1 Canopy size

Canopy size was measured on four occasions during the growing season, on 3 February at tillering (GS 22-24), 11 April the start of stem extension (GS 30), 25 May prior to ear emergence (GS 49) and after the application of the foliar urea treatments on 13 June. Figure 4.1 shows the changes in the GAI that occurred during this time. The N0 canopy grew slowly and only attained a GAI of 1.8 by anthesis. The GAI 5 crops reached their target index of 5 (5.1) by ear emergence on 25 May, and at this time there was no significant difference between the GAI of these crops and that of the Ncf crop (5.2). Both the GAI 5 and the Ncf crops maintained their GAI until the end of anthesis on 19 June. It should be noted that all the GAIs measured were smaller than might normally be expected, GAIs as large as eight are quite frequent under conventional fertilization techniques.

4.2.2 Crop growth

Shoot number was measured on the same occasions as GAI, on 3 February at tillering (GS 22-24) before N was applied, on 11 April after basal-N had been applied, at the start of stem extension (GS 30) and on 25 May prior to ear emergence (GS 49) before the application of the late-N treatments.

Table 4.2 Shoot number m^{-2} and crop biomass ($g\ m^{-2}$) measured on three occasions at IACR-Rothamsted in 1995.

Treatment	**3 February**		**11 April**		**25 May**	
	Shoot No.	Biomass	Shoot No.	Biomass	Shoot No.	Biomass
N0	533	36.6	435	86.0	297	330.9
GAI 5	533	36.6	419	92.0	406	538.1
Ncf	533	36.6	513	145.0	407	612.9
SED (6 df)	-	-	99.7	38.6	59.5	72.9

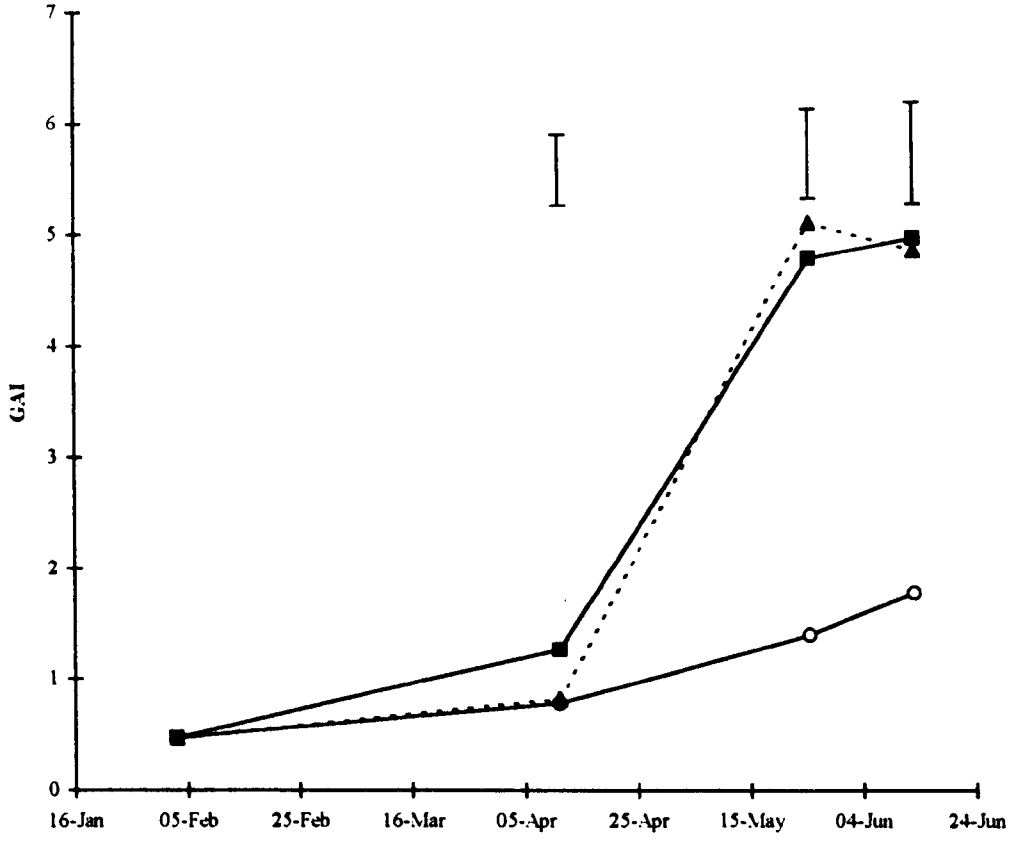


Figure 4.1 The change in GAI between tillering (GS 22-24) on 3 February and anthesis (GS 65) on 13 June at IACR-Rothamsted in 1995. ○ N0 crop, ▲ GAI 5 crop and ■ Ncf crop. The SEDs shown have 6 df.

Shoot number m^{-2} declined progressively from 533 on 3 February to 297 on 25 May in the N0 crop, and to 406 shoots m^{-2} in both the GAI 5 and Ncf crops. N fertilizer was not applied until 16 March and although by 11 April the crops had responded to the N there was no significant difference between the biomass of the N0 and GAI 5 crops. On 25 May the biomass of the N0 crop was significantly smaller ($P = 0.01$), than that of the GAI 5 and Ncf crops between which there were no significant differences. There was no significant increase in the amount of N present in the crops between tillering (16.5 kg N ha^{-1}) and the start of stem extension when 16.6, 18.8 and 29.1 kg N ha^{-1} were present in the N0, GAI 5 and Ncf crops respectively and between which there were no significant differences (SED = 5.48, 6 df).

4.2.3 Flag leaf chlorophyll content and canopy senescence

The effects of both basal N and late-N treatment on the prolongation of GAI were assessed by a series of indirect measurements of the chlorophyll content of the flag leaves, made using a SPAD chlorophyll meter (Minolta, Japan). Initial measurements were made just prior to ear emergence and continued on a weekly basis until canopy senescence did not permit further measurement. The data have do not have units but were standardised to allow comparisons, by the measurement of a slide with a known SPAD reading which acted as a "control".

Table 4.3 SPAD meter readings of the relative "chlorophyll content" of the flag leaves between ear emergence and anthesis at IACR-Rothamsted 1995.

Treatment	25 May	1 June	7 June
N0	31.9	30.6	29.8
GAI 5	45.2	46.8	48.0
Ncf	48.5	51.1	52.6
SED (4 df)	0.848	1.375	1.109

For comparisons between sample dates SED = 1.044, 16 df.

The flag leaves of the N0 crop contained significantly less chlorophyll and the Ncf crop significantly more than those of the GAI 5 crop, ($P = 0.001$). There was no significant difference in "chlorophyll content" of the flag leaves of the N0 crop between the three occasions, but both the GAI 5 and the Ncf crops showed a significant increase between 25 May and 7 June, $P = 0.01$. Subsequent measurements were restricted to only one replicate as it was not possible to measure all of the blocks during the early morning before the leaves became flaccid or had rolled because of the particularly hot weather conditions. These factors affect the readings obtained from the SPAD meter (I. Pearman, personal communication). Figure 4.2 illustrates the values obtained for each of the 13 separate basal and late-N treatments that were measured. The shape of the graphs suggest there were no obvious differences in the effects of the late-N foliar urea treatments applied to GAI 5 crops, only that the "chlorophyll content" was higher than when late-N had not been applied. Late-N applied to the N0 and Ncf crops seemed to increase the "chlorophyll content" of the flag leaves and may therefore have prolonged the retention of green area.

Table 4.4 shows the "chlorophyll content" of the flag leaves on 13 July, the last day on which realistic measurements were possible because of subsequent leaf senescence. There was no significant difference in the "chlorophyll content" of the flag leaves of the N0 crops and the GAI 5 crop that did not receive late-N when measured on 13 July. Applying foliar urea to a GAI 5 crop significantly increased the "chlorophyll content" of the flag leaves compared to the GAI 5 crop that did not receive late-N, ($P = 0.001$). Foliar urea did not significantly increase the "chlorophyll content" of the flag leaves of the N0 crop but it did significantly increase that of the Ncf crop ($P = 0.001$).

Leaf chlorophyll content was significantly improved by the application of the adjuvants prior to ear emergence, ($P = 0.001$) irrespective of the adjuvant applied. The spreader, Silwet L-77 increased leaf "chlorophyll content" when applied at anthesis and at ear emergence. The sticker (Spray-Fix) and the penetrant (LI-700) also improved the "chlorophyll content" of the flag leaves compared to when foliar urea was applied without an adjuvant. The application of 60 kg N ha^{-1} as foliar urea at anthesis significantly increased the "chlorophyll content" of the flag leaves compared to when 30 kg N ha^{-1} was applied.

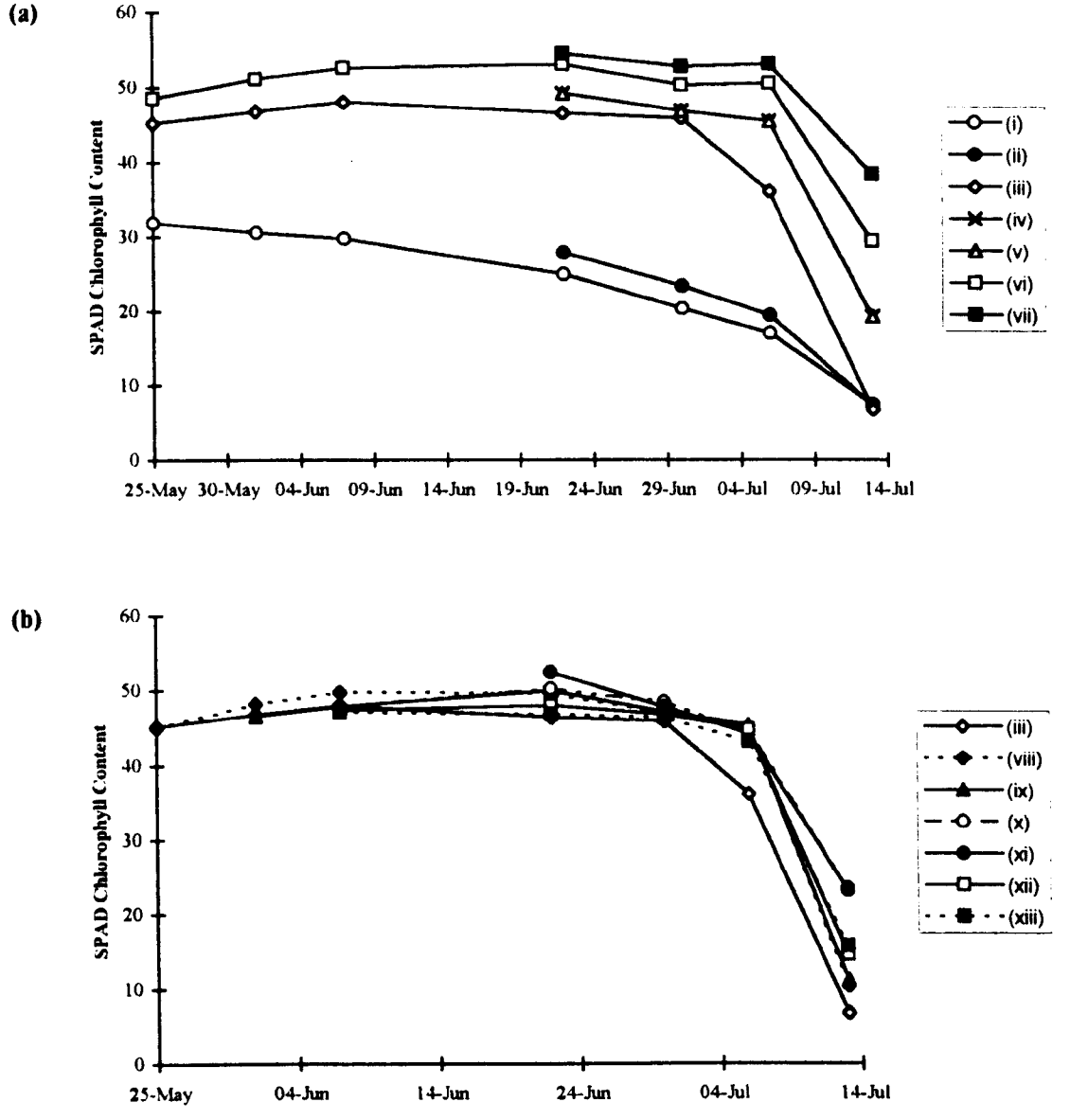


Figure 4.2 The change in SPAD "chlorophyll content" of the flag leaves of crops receiving late-N as foliar urea at (a) flag leaf emergence and prior to ear emergence, and (b) at anthesis. (i) N0 (ii) N0 + 30 kg N ha^{-1} anthesis (iii) GAI 5 (iv) GAI 5 + 30 kg N ha^{-1} anthesis (v) GAI 5 + 60 kg N ha^{-1} anthesis (vi) Ncf (vii) Ncf + 30 kg N ha^{-1} anthesis (viii) GAI 5 + 30 kg N ha^{-1} flag leaf emergence (ix) GAI 5 + 30 kg N ha^{-1} ear emergence (x) GAI 5 + 30 kg N ha^{-1} with 0.1 % Silwet L-77 ear emergence (xi) GAI 5 + 30 kg N ha^{-1} with 0.1 % Silwet L-77 anthesis (xii) GAI 5 + 30 kg N ha^{-1} with 0.1 % Spray-Fix ear emergence (xiii) GAI 5 + 30 kg N ha^{-1} with 0.1 % LI-700 ear emergence

Table 4.4 The SPAD "chlorophyll content" of the flag leaves on 13 July (GS 85), (values are the means of three replicates) and the date on which the canopies finally died at IACR-Rothamsted 1995.

Treatment	13 July	Senescence Completed
N0 - no late-N applied	7.3	21 July
N0 + 30 kg N ha^{-1} at anthesis	7.6	22 July
GAI 5 - no late-N applied	7.8	23 July
GAI 5 + 30 kg N ha^{-1} at flag leaf emergence	10.6	23 July
GAI 5 + 30 kg N ha^{-1} at ear emergence	11.6	23 July
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	22.6	23 July
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	14.3	23 July
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	16.0	23 July
GAI 5 + 30 kg N ha^{-1} at anthesis	19.2	23 July
GAI 5 + 60 kg N ha^{-1} at anthesis	22.0	23 July
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	14.5	23 July
Ncf - no late-N applied	30.7	26 July
Ncf + 30 kg N ha^{-1} at anthesis	36.9	27 July
SED (24 df)	0.816	-

Visual assessments of canopy green area were made from 17 July to determine the point at which the canopy died completely. The N0 crops were the first to lose all their green area. It was not possible to differentiate the late-N treatments applied to the GAI 5 canopies as despite the differences in "chlorophyll content" measured on 13 July, the canopies died on the same day in the very hot summer. Senescence was rapid and the Ncf crops retained their green area for a further four days after the senescence of the GAI 5 crops.

4.2.4 Weather conditions

Figure 4.3 (a) shows the mean daily minimum and maximum temperature (°C), incident radiation (MJ m^{-2}) and hours of sunshine and Figure 4.3 (b) shows the total monthly rainfall (mm) and the wind speed (km h^{-1}) for the period 1 September 1994 to 31 August 1995. The data show that there were no extreme weather conditions during the year and that the beginning of July which was warm and sunny and was probably an additional factor resulting in the rapid senescence of the crop canopies.

4.3 YIELD

The yields of grain from this experiment were considerably greater than those obtained from the 1994 experiment and comparable with those normally expected from this variety and site.

4.3.1 Hand harvest yields

Hand harvest samples were taken on 3 August 1995, and the yields obtained are shown in Table 4.5. The N0 crops and the GAI 5 crop that did not receive late-N as foliar urea yielded significantly less grain, chaff and straw than all the other treatments ($P = 0.01$). The application of late-N to the N0 and Ncf crops did not significantly increase yields and the yield of the Ncf crop was not significantly different to that of the GAI 5 crops receiving late-N. Applications of foliar urea to the GAI 5 crops significantly increased yield irrespective of when it was applied, the amount applied, or whether an adjuvant had been used. It did not increase the yields of chaff or straw.

4.3.2 Harvest index

The harvest indices for grain, chaff and straw are shown in Table 4.5. Approximately 55 % of the total biomass was partitioned to the grain, less than 10 % to the chaff and 35 % to the straw.

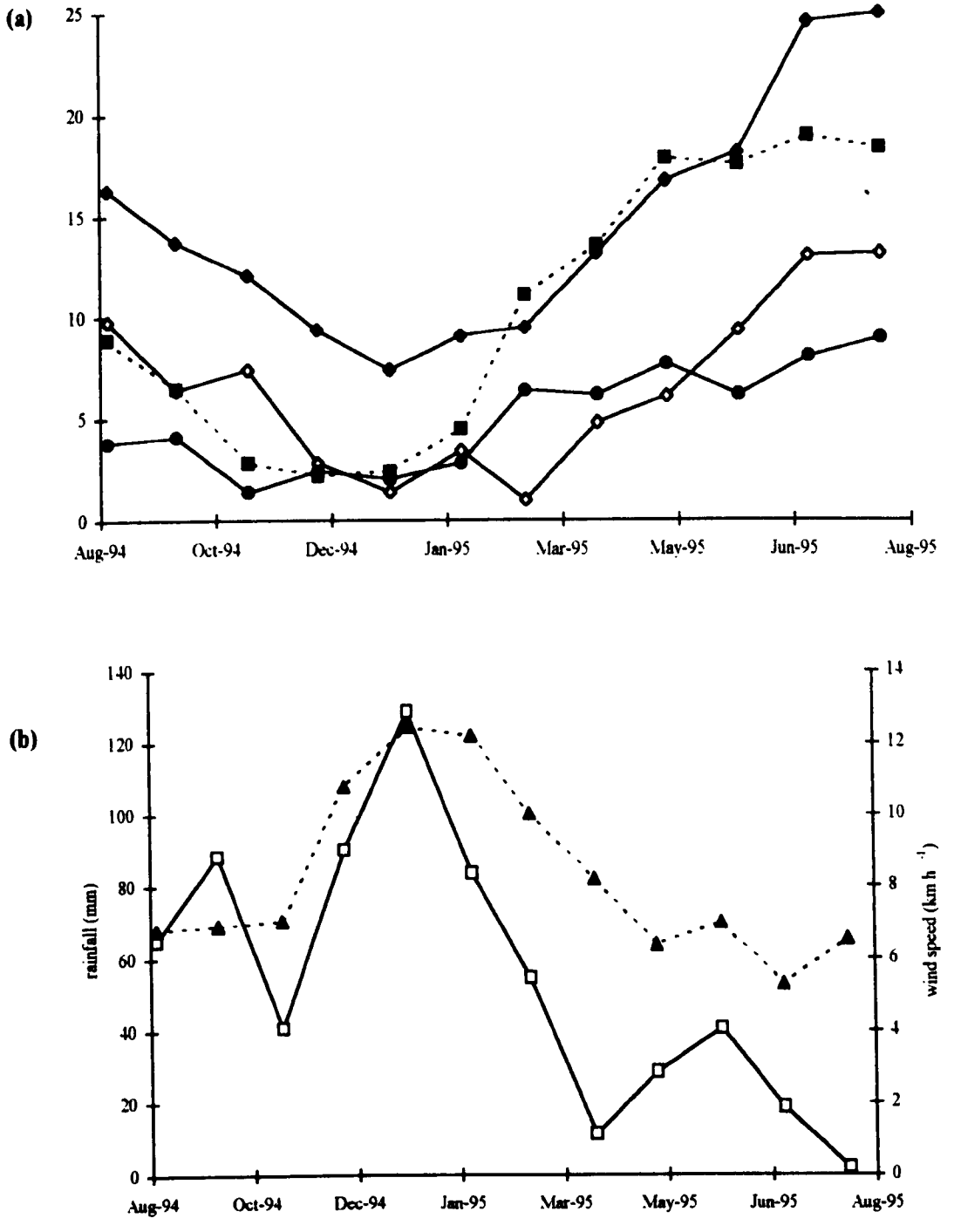


Figure 4.3 (a) mean daily minimum (◊) and maximum temperature, °C (◆), hours of sunshine (●) and incident radiation, MJ m^{-2} (■) and 4.3 (b) total monthly rainfall, mm (□) and wind speed, km h^{-1}(▲) for the period 1 September 1994 to 31 August 1995 at IACR-Rothamsted.

Table 4.5 Hand harvest components of yield (t ha^{-1}, 100 % and 85 % DM), percentage harvest indices and thousand grain weight (g) at IACR-Rothamsted 1995.

Treatment	100 % DM				85 % DM	Harvest Indices			
	Grain	Chaff	Straw	Total	Grain	Grain	Chaff	Straw	TGW
N0 - no late-N applied	3.37	0.67	2.71	6.75	3.97	49.9	9.99	40.0	37.78
N0 + 30 kg N ha^{-1} at anthesis	3.33	0.60	2.45	6.38	3.91	52.3	9.43	38.2	39.44
GAI 5 - no late-N applied	6.02	1.20	4.13	11.35	7.08	53.0	10.6	36.4	39.28
GAI 5 + 30 kg N ha^{-1} at flag leaf emergence	7.63	1.39	5.01	14.03	8.98	54.3	9.94	35.8	40.46
GAI 5 + 30 kg N ha^{-1} at ear emergence	7.49	1.28	4.86	13.63	8.81	54.9	9.40	35.7	41.64
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	7.02	1.25	4.49	12.76	8.26	55.2	9.77	35.1	40.65
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	7.71	1.37	5.06	14.14	9.08	54.6	9.70	35.7	40.44
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	7.07	1.28	4.49	12.84	8.31	55.1	9.97	34.9	41.05
GAI 5 + 30 kg N ha^{-1} at anthesis	7.12	1.31	4.68	13.11	8.37	54.3	10.0	35.7	40.54
GAI 5 + 60 kg N ha^{-1} at anthesis	7.40	1.29	4.76	13.45	8.70	54.9	9.63	35.5	40.05
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	7.85	1.34	4.86	14.05	9.23	55.3	9.56	34.7	40.86
Ncf - no late-N applied	7.57	1.42	4.90	13.89	8.90	55.9	9.93	34.2	40.59
Ncf + 30 kg N ha^{-1} at anthesis	8.29	1.42	4.99	14.70	9.75	56.4	9.68	33.9	42.55
SED (24 df)	0.585	0.101	0.387	0.992	0.689	1.130	0.369	1.147	0.888

The increasing amounts of basal N applied significantly increased the grain HI and significantly decreased straw HI, ($P = 0.001$), chaff HI was not affected by the amount of basal N applied. The application of late-N as foliar urea to the N0 crop only significantly increased grain HI ($P = 0.001$), but when applied to the GAI 5 and Ncf crops had no significant effect on either grain, chaff or straw HI, irrespective of the timing of application, the amount of N applied or whether an adjuvant was used.

4.4 GRAIN QUALITY

4.4.1 **Thousand grain weight**

The data for thousand grain weight are shown in Table 4.5. TGW increased with the increasing amount of basal N applied, but the differences were not significant. The application of late-N as foliar urea did not significantly increase TGW when applied to the N0 and GAI 5 crops, except when 30 kg N ha^{-1} was applied at ear emergence without the addition of an adjuvant. Only when late-N was applied to the Ncf crop was a significant increase recorded, ($P = 0.001$).

4.4.2 **Grain N percentage**

The application of basal N fertilizer significantly increased the percentage N content of the grain, Table 4.6. The application of foliar urea significantly increased percentage N content for all the basal N crops in all instances. There were no significant differences in the effectiveness of the late-N treatments applied to the GAI 5 crops, only the Ncf crops produced grain that exceeded a protein content of 11 %.

4.5 N PRESENT IN THE CROP AT HARVEST

4.5.1 Total N content of the crop

Total N offtake by the crop, the N present in the grain, chaff and straw and the percentage N HI of the hand harvested samples is shown in Table 4.6.

As the amount of basal N applied increased, the amount of N in the crop components and the total amount of N present increased significantly ($P = 0.001$). The N content of the grain of the N0 crop was significantly smaller than that of the GAI 5 and Ncf crops which were not significantly different from each other. The application of late-N as foliar urea did not significantly alter the N content of the N0 crop, but did significantly increase the N contents of the grain and straw in the GAI 5 crop irrespective of the amount applied, the timing of application or whether an adjuvant was used ($P = 0.001$), and increased grain N in the Ncf crop. Late-N did not affect the amount of N in the chaff.

The percentage N HI of the grain of the N0 crop was significantly smaller than the GAI 5 and Ncf crops and, except for the N0 crop, percentage N harvest indices were not significantly increased by late applications of foliar urea. The values for percentage N HI, at greater than 85 %, were higher than might be expected for the GAI 5 and Ncf crops.

4.5.2. Percentage apparent N recovery

The percentage apparent N recovery was calculated as total N in the crop minus total N in the N0 crop divided by total amount of N fertilizer applied and is shown in Table 4.7. This indicates the amount of N fertilizer taken up by the crop and excludes any N present in the soil before fertilizer was applied or N mineralized in the soil during the growing season. The N0 crop contained a total of 52 kg N ha^{-1} at harvest, 12 kg more than the 40 kg N ha^{-1} that was measured as present in the crop and the soil in February. The percentage apparent N recovery of the basal N crops increased significantly as the amount of N applied

increased. The late-N applied to the N0 crop was used the least effectively, with only 12.7 % of the 30 kg N ha^{-1} that was applied taken up. The application of late-N as foliar urea to a GAI 5 crop at flag leaf emergence and ear emergence and with the addition of Spray-Fix at ear emergence and Silwet L-77 at anthesis resulted in a significant increase in the amount of N recovered by the crop ($P = 0.01$), other late-N treatments applied did not significantly improve recovery. The Ncf crop which received a supplementary 50 kg N ha^{-1} (as ammonium nitrate) in May in addition to late-N as foliar urea, recovered a smaller amount of N than the Ncf crop which did not receive late or supplemental N but the amounts recovered were not significantly different.

Table 4.6 % N in the grain, the amount of N present in the grain, chaff and straw (kg ha^{-1}), total N offtake (kg ha^{-1}) and the percentage N HI of the grain at IACR-Rothamsted 1995.

Treatment	% N	Grain	Chaff	Straw	Total	% N HI
N0 - no late-N applied	1.286	43.4	2.26	6.25	52.0	83.6
N0 + 30 kg N ha^{-1} at anthesis	1.438	47.8	2.04	5.99	55.8	85.7
GAI 5 - no late-N applied	1.592	95.7	5.83	9.77	111.3	86.0
GAI 5 + 30 kg N ha^{-1} at flag leaf emergence	1.806	138.3	6.40	13.49	158.2	87.4
GAI 5 + 30 kg N ha^{-1} at ear emergence	1.805	135.1	5.39	13.11	153.6	87.9
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	1.793	126.1	5.50	13.11	144.8	87.2
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	1.698	131.1	5.92	14.42	151.4	86.6
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	1.772	125.3	5.32	11.84	142.5	88.0
GAI 5 + 30 kg N ha^{-1} at anthesis	1.730	123.1	6.44	13.15	142.7	86.2
GAI 5 + 60 kg N ha^{-1} at anthesis	1.824	135.0	6.38	12.62	154.0	87.6
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	1.770	138.7	5.39	12.86	156.9	88.3
Ncf - no late-N applied	2.052	155.4	7.46	16.43	179.3	86.7
Ncf + 30 kg N ha^{-1} at anthesis	2.139	177.2	7.32	16.13	200.7	88.4
SED (24 df)	0.0473	11.44	0.870	1.324	12.82	0.965

Table 4.7 The amount (kg N ha^{-1}) as basal or late N fertilizer applied and the total amount taken up (kg ha^{-1}) and the percentage apparent N recovered by the crop at IACR-Rothamsted in 1995.

Treatment	Basal N Applied	Late-N Applied	Total N Applied	Total N Uptake	% Apparent N Recovery
N0 - no late-N applied	0	0	0	52.0	-
N0 + 30 kg N ha^{-1} at anthesis	0	30	30	55.8	12.7
GAI 5 - no late-N applied	120	0	120	111.3	49.4
GAI 5 + 30 kg N ha^{-1} at flag leaf emergence	120	30	150	158.2	70.8
GAI 5 + 30 kg N ha^{-1} at ear emergence	120	30	150	153.6	67.7
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	120	30	150	144.8	61.9
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	120	30	150	151.4	66.3
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	120	30	150	142.5	60.3
GAI 5 + 30 kg N ha^{-1} at anthesis	120	30	150	142.7	60.4
GAI 5 + 60 kg N ha^{-1} at anthesis	120	60	180	154.0	56.7
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	120	30	150	156.9	69.9
Ncf - no late-N applied	200	0	200	179.3	63.7
Ncf + 30 kg N ha^{-1} at anthesis	250	30	280	200.7	53.1
SED (24 df)	-	-	-	12.82	6.84

4.5.3 Recovery of late-N

Table 4.8 shows the percentage recovery and the amount (kg N ha^{-1}) of late-N, applied as foliar urea, recovered from applications made to N0, GAI 5 and Ncf crops. This was calculated as the difference in the total N content of the whole crop and the N content of the grain of the basal N crops that did not receive late-N and the corresponding crops that did. There were no significant differences in the amount of late-N recovered at harvest in either the grain or in total by the GAI 5 crops or the Ncf crop. The N0 crop recovered a significantly smaller percentage of late-N in the grain than the other crops and there were no significant differences between the remaining treatments. However, despite this, a large proportion of the late-N was recovered by the GAI 5 and Ncf crops, in some cases greater than 100 % of the amount applied.

Table 4.8 The amount (kg N ha^{-1}) and the percentage of foliar urea recovered in the grain and in the whole plant measured at harvest at IACR-Rothamsted in 1995.

Treatment	N Recovered in the grain (kg ha^{-1})	% N Recovered in the grain	Total N Recovered (kg ha^{-1})	% Total N Recovered
N0 + 30 kg N ha^{-1} at anthesis	4.2	13.2	3.8	10.4
GAI 5 + 30 kg N ha^{-1} at flag leaf emergence	42.7	142.2	47.0	156.5
GAI 5 + 30 kg N ha^{-1} at ear emergence	39.4	131.3	42.3	141.1
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	30.5	101.5	33.5	111.5
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	35.4	118.0	40.1	133.8
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	29.7	98.9	31.2	104.0
GAI 5 + 30 kg N ha^{-1} at anthesis	27.4	91.3	31.4	104.6
GAI 5 + 60 kg N ha^{-1} at anthesis	27.5	45.8	42.8	71.2
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	43.0	143.2	45.7	152.2
Ncf + 30 kg N ha^{-1} at anthesis	21.8	72.8	21.4	71.2
SED (17 df)	11.4	36.80	13.72	42.68

4.6 DISCUSSION AND CONCLUSIONS

The late-N treatments of foliar urea were applied to the crops at specific growth stages. The initial intention was to apply each of the treatments on the same day or on consecutive days but this was not always possible due to wind speeds which were sufficient to prevent spraying, resulting in up to seven days between applications recorded as being made at the same growth stage. It is possible that the comparisons between the treatments and the treatment effects of applications at a specific growth stage may have been influenced by the different dates of application especially as they were subject to different weather conditions during and after spraying. However, the differences in the weather conditions were not great enough to suggest that this would have been an important factor. Differences between treatments may also have been caused by the change in physiological growth stage of the plants, although this would probably not have been particularly great between, for example GS 61 and 68 during anthesis. Comparisons have therefore been made between treatments applied at the same growth stage *i.e.* at ear emergence and anthesis and between different growth stages.

4.6.1 **Prolongation of green area index**

Unlike the field experiment at IACR-Rothamsted in 1994, this experiment was not affected by weeds. Maximum canopy size was attained by ear emergence and was 5.1 for the GAI 5 crops and 5.2 for the Ncf crop, suggesting that N may not have been a limiting factor for growth. Canopy senescence did not begin to have a significant effect upon GAI until after anthesis when N was retranslocated to the grain. Leaf senescence began earlier in the N0 crop than other crops (at ear emergence, 1 June) measured by a change in the readings of SPAD chlorophyll content of the flag leaves. The application of foliar urea at anthesis to the N0 and Ncf crops increased the chlorophyll content of the flag leaves by only a small amount and did not significantly delay the senescence of the canopy. Although it was not possible to fully assess the influence of canopy size on the effectiveness of the foliar urea treatments as the GAI 5 and Ncf crops were so similar in size, it did indicate that

the foliage was capable of taking up and utilizing foliar urea whatever its N status. The N0, GAI 5 and Ncf crops contained 44.9, 154.2 and 200.5 kg N ha^{-1} at anthesis respectively and all showed an increase in SPAD chlorophyll content after the application of foliar urea, allowing the assumption to be made that N was taken up from them.

The readings of SPAD chlorophyll content of the flag leaves showed that there were no significant differences in the effectiveness of the treatments to maintain leaf chlorophyll and by assumption, the prolongation of the green area of the GAI 5 crops. All the late-N treatments applied improved the duration of the green area between 30 June and 6 July and all had significantly higher chlorophyll contents on 13 July (the last day on which chlorophyll content was measured) compared to the GAI 5 crop that did not receive late-N. The late-N may either have prevented senescence by replacing the N that would otherwise be retranslocated to the grain or by being assimilated and transported directly to the grain as a source of N for protein accumulation.

The late application of 60 as compared to 30 kg N ha^{-1} as foliar urea at anthesis increased the SPAD chlorophyll content of the flag leaf measured on 13 July, but did not greatly delay canopy senescence. The use of the adjuvants in the spray solutions did not have any effect upon the rate at which green area declined, but did increase the SPAD chlorophyll content on the 13 July.

4.6.2 Grain yield and quality

Grain yields from the N0 crops were significantly lower than from the N fertilized crops and the yield of the GAI 5 crops that received late-N were similar to those of the Ncf crops. Foliar urea applied to both the N0 and Ncf crops did not increase grain yields or the protein content of the grain; the grain of the N0 crop did not reach the market threshold for bread making quality (11 %). In this case there was probably insufficient N available for the production of protein irrespective of the yield. Well fertilized crops that produce high yields do not always attain the threshold protein content as during grain filling,

carbohydrate accumulation increases, which may result in a dilution of the protein content. The ratio of grain to straw increased with increasing amounts of basal N fertilizer applied and was not affected by the late-N applications.

There is some evidence, that late-N applications made to improve grain protein content can depress grain yields, in addition to the well established trade-off between yield and grain protein content, such that higher protein contents are not generally produced from higher yielding crops (Smith *et al.*, 1991; Sarandon and Gianibelli, 1990 and Grama *et al.*, 1987). In this case late-N applied as foliar urea to GAI 5 crops increased yield, with the earlier applications at flag leaf emergence and ear emergence, having a greater effect on yield and N content (kg ha^{-1}) than applications made at anthesis. This resulted in the grain from crops given late-N at anthesis not reaching the market threshold for protein. There are two possible reasons for this: first, the plant was in a better position at flag leaf emergence to take up more of the late-N having younger leaves with thinner cuticles (Franke, 1986) and secondly, an early application prevented N becoming a limiting factor during the formation of the ear, anthesis and grain filling. The later application at anthesis might not have fully compensated for the previous lack of N and the plant did not have sufficient time to make up for this before senescence was complete. Another factor that may be important is photosynthetic rate, which may have been reduced or limited in the plots that did not receive late-N until anthesis.

The application of 60 kg N ha^{-1} as foliar urea at anthesis resulted in the greatest increase in the grain N concentration, its effects being similar to those of foliar urea applied during the milky ripe stage of development to ensure that there is sufficient protein in the grain to exceed the threshold for bread making quality grain. A significant increase in yield was also recorded, but this was smaller than from other foliar urea applications; similar examples are reported in the literature by Smith *et al.*, (1991). This larger application contained sufficient N both to prolong the GAI of the canopy, resulting in a higher chlorophyll content of the flag leaves on 13 July and also to increase the percentage N content of the grain. However, the grain from this crop did not quite reach the market threshold of 11 %

protein for bread making quality grain, the protein content was 10.4 %, but none of the other GAI 5 crops exceeded this level either. There may not have been enough N available to these crops to sufficiently fill the grain and maintain both yield and quality, whilst also maintaining the duration of the canopy green area. Only the Ncf crops contained sufficient N in the grain to produce grain suitable for bread making.

The increased SPAD chlorophyll content of the flag leaves of GAI 5 crops that received foliar urea (late-N) with an adjuvant, at either ear emergence or anthesis was not always accompanied by increases in yield or N content. Late-N treatments applied to GAI 5 crops that resulted in higher grain yields, such as Silwet L-77 at anthesis or Spray-Fix at ear emergence, did not always have a corresponding increase in grain percent N content. There may have been a trade-off between protein content (percentage N content) and grain yield, where the number and size of grains increased whilst the protein content decreased.

4.6.3 N uptake

Table 4.6 shows the total amount of N taken up by the crops. The amount of basal N applied had a significant effect upon the N content of the crop at final harvest. The N0 crop contained significantly less N than the GAI 5 and Ncf crops and whilst the application of late-N as foliar urea to an N0 crop did not significantly increase the total amount present, it did increase the percentage N content of the grain. Late-N applied to the Ncf crop which also received an additional 50 kg N ha^{-1} to ensure that there was sufficient N available to it, did not result in a significant increase in N content, possibly because there was insufficient moisture in the soil to allow uptake at the appropriate time.

The other point to note from Table 4.6 is that late-N as foliar urea increased the N contents of the GAI 5 crops by more than the amount of N applied (*i.e.* 30 kg N ha^{-1}) and this is supported by the data in Table 4.8 which show that for some treatments more than 100 % of the applied late-N was recovered both in the grain and in total in the whole crop. This may simply be the result of a sampling error resulting from an artificially low N content of

the GAI 5 crop that did not receive late-N, since N contents were measured from only a small sample of 100 shoots. Alternatively, the late-N foliar urea treatments may have stimulated the previously N deficient crops to take up more N from the soil. It was suggested earlier that foliar applied N was transported directly to the ear, either via the xylem as nitrate or amino acids, or as amino acids in the phloem. Movement in the xylem is driven by evapotranspiration which may stimulate the uptake of N by the roots. It is also possible that the delay in the senescence of the canopy brought about by the application of foliar urea might have maintained uptake from the soil, when it might otherwise have been curtailed. When 60 kg N ha^{-1} was applied it is probable that only a limited amount of N was taken up from the application, possibly just over half and the additional N present was also as a result of increased uptake from the soil. It is notable that Gooding *et al.* (1991), Smith *et al.* (1987) and Sylvester-Bradley *et al.* (1984) found that foliar urea only produced increases in grain yield when the crop had been insufficiently fertilized in the spring, perhaps suggesting that these crops would also take up more N under these circumstances. The N content of the basal GAI 5 crop was significantly lower than that of the Ncf crop (before late-N was applied to either), therefore it is likely that the Ncf crop already contained sufficient N to fulfil its yield potential and adequately fill the grains. Consequently only a small proportion of the additional late-N was recovered by the Ncf crop as only a small amount was required and the late-N applied to the GAI 5 crops compensated for the smaller amount of basal N available to the GAI 5 crops.

The reproductive phase of growth, which starts at anthesis, increases competition for carbohydrates and leads to a reduction in root activity and nutrient uptake (Marschner, 1995) and foliar nutrient applications have been found to compensate for this. For nitrogen, evidence is limited to the legume soybean, in which the late applications of N at flowering delayed leaf senescence and allowed N fixation in the nodules to continue by maintaining the supply of carbohydrates to both roots and nodules (Ikeda, Choi and Yamada, 1991). Batten and Wardlaw (1987) found a similar effect in wheat, with foliar applications of phosphorus. Applying this to the data in Table 4.7, for the apparent recoveries of the applied N, the GAI 5 crops that did not have late-N applied, recovered

less than half the available N, whereas those receiving late-N recovered approximately 60 to 70 % of the available N, suggesting that soil uptake may have been stimulated by these late applications of N.

Therefore the application of late-N as foliar urea to the GAI 5 crops increased the "chlorophyll content" of the flag leaves and by assumption the duration of the GAI after anthesis, but did not have any influence upon the date of complete senescence. This resulted in larger yields, an increase in the percentage N content of the grain producing higher protein contents, a greater total N uptake and the more efficient use of N.

Chapter 5: RESULTS OF THE FIELD EXPERIMENT AT SUTTON BONINGTON 1995

The aims of the experiment were to compare directly the effects of foliar urea applied at anthesis to N0, GAI 5 and Ncf crops and also to provide combine harvest yields and GAI measurements for some of the treatments that were being applied in the same year at IACR-Rothamsted.

5.1 EXPERIMENTAL DESIGN AND TREATMENTS APPLIED

The treatments were non-factorial and fully randomised within three replicate blocks. They consisted of four basal N treatments (N0, GAI 3, GAI 5 and Ncf), and nine late-N treatments superimposed on the basal N treatments.

The experiment was sown on 6 October 1994 and the crop husbandry methods used in the experiment are shown in Appendix 1.

A similar procedure to that used at IACR-Rothamsted in 1995 was used to calculate basal N fertilizer requirement. 55 kg N ha^{-1} was present in the crop in March and 27 kg N ha^{-1} in the soil. This was almost sufficient to produce a canopy of GAI 3 without additional fertilizer being applied, but in order to differentiate it from the N0 crop 30 kg N ha^{-1} was applied. The GAI 5 crop received 120 kg N ha^{-1} and the Ncf crop 175 kg N ha^{-1}. The N required by the Ncf crop was calculated from past crop and yield response curves to N at Sutton Bonington, adjusted for sowing date, previous cropping and expected yield, in accordance with standard ADAS recommendations. The fertilizer N was applied as split dressing of 30 kg N ha^{-1} prilled ammonium nitrate on 4 April 1995 with the balance applied on 28 April 1995.

5.1.1 Late-N treatments

The foliar urea treatments were applied using a tractor-mounted hydraulic sprayer (Allman Spraymaster Minor) fitted with Lurmark 05-F110 nozzles (yellow) at 2.7 km h^{-1}, and 2.6 bar pressure. 60 kg N ha^{-1} was applied at anthesis, as two applications of 30 kg N ha^{-1} in 400 l ha^{-1} water on 20 and 27 June 1995 to reduce the risk of leaf scorch. The same rate of prilled ammonium nitrate was also applied to the soil of the N0 crop to provide a comparison in the effectiveness of the two methods of late-N application. The treatments applied are shown in table 5.1, all treatments were applied during anthesis (GS 61-65) and on 20 and 27 June unless otherwise stated.

Table 5.1 Late-N treatments applied to the field experiment at Sutton Bonington 1995.

Target Canopy	Treatment
N0	no late-N applied
N0	60 kg N ha^{-1} prilled ammonium nitrate
N0	60 kg N ha^{-1} foliar urea
GAI 3	no late-N applied
GAI 3	60 kg N ha^{-1} foliar urea
GAI 5	no late-N applied
GAI 5	60 kg N ha^{-1} foliar urea
GAI 5	30 kg N ha^{-1} foliar urea on 8 June 1995
GAI 5	30 kg N ha^{-1} foliar urea on 20 June 1995
GAI 5	30 kg N ha^{-1} foliar urea + 0.1 % Silwet L-77
GAI 5	30 kg N ha^{-1} foliar urea + 0.1 % Spray-Fix
Ncf	no late-N applied
Ncf	60 kg N ha^{-1} foliar urea

5.2 CANOPY GROWTH AND GREEN AREA PROLONGATION

5.2.1 Crop growth

Measurements of GAI were made on three occasions during the season, the first on 18 May 1995 at flag leaf emergence (GS 39), the second on 20 June towards the end of anthesis when the N0 and GAI 3 canopies were already starting to senesce, and the last on 17 July when the GAI of the canopies were declining. Shoot numbers were counted only on 18 May, the numbers of fertile and infertile shoot were counted separately. Total crop biomass (g m^{-2}) was also measured at this time (table 5.3).

Table 5.2 GAI measured on three occasions during growth at Sutton Bonington 1995.

Treatment	18 May	20 June	17 July
N0	2.74	1.10	0.55
GAI 3	3.66	2.90	0.72
GAI 5	3.96	3.68	1.57
Ncf	3.70	4.52	1.88
SED (6 df)	0.465	0.237	0.208

The maximum measured GAIs were 2.7 in the N0 crop, 3.7 in the GAI 3 crop, 4.0 in the GAI 5 crop and 4.52 in the Ncf crop. Maximum GAI appeared to be achieved later in the season for the Ncf crop and the GAI of the N0 and GAI 3 crops decreased earlier in the season than for the GAI 5 and Ncf crops. These values were also smaller than would normally be expected, GAIs of 7 or 8 are common under conventional fertilization practices however, the number of shoots m^{-2} also contributes to GAI, each shoot accounting for approximately 120 cm^2 (D.T. Stokes, personal communication). Smaller numbers of shoots will result in a lower GAI.

Figure 5.1 shows the effect of applying late-N to the four basal N crops, measured on 17 July 1995. Foliar urea significantly increased the GAI of the N0 and Ncf crops ($P = 0.01$),

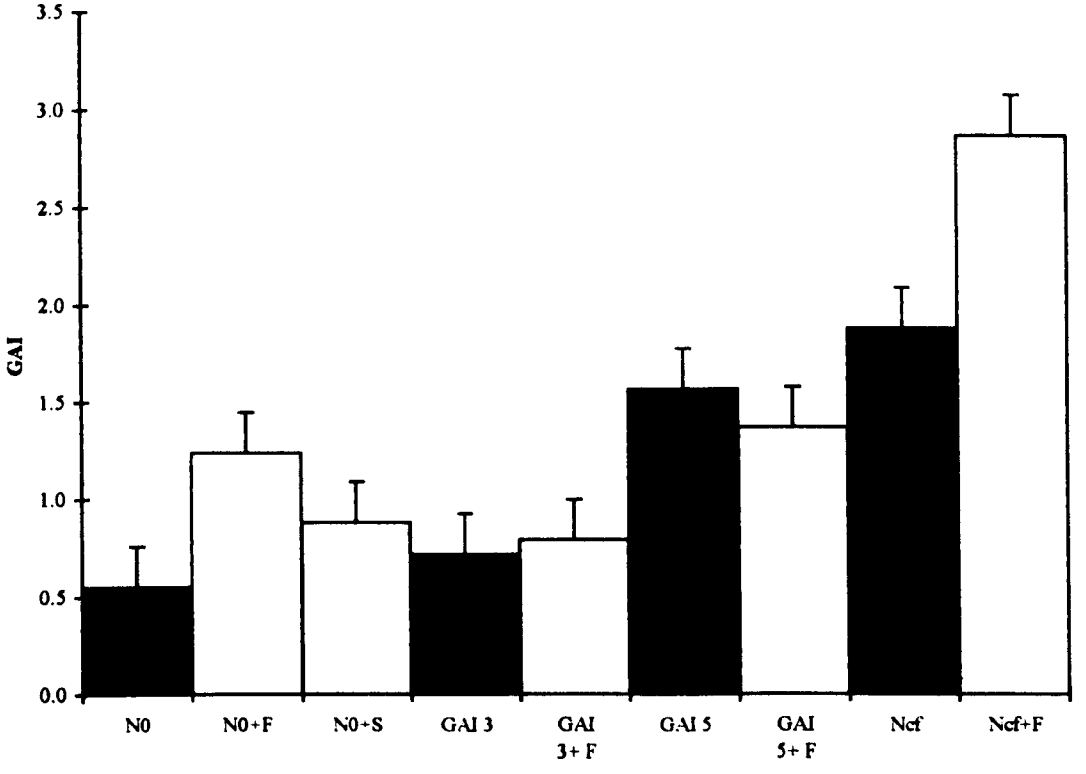


Figure 5.1 The GAI of the four basal N crops after the application of late-N as either foliar urea (+ F) or as solid ammonium nitrate to the soil (+ S), measured on 17 July 1995 at Sutton Bonington. The SEDs shown have 24 df.

but did not affect the GAI 3 or GAI 5 crops. Solid ammonium nitrate applied to the N0 crop did not significantly increase GAI probably because there was insufficient rainfall after application to allow uptake by the crop.

Table 5.3 Fertile and infertile shoot number m^{-2} and crop biomass ($g\ m^{-2}$) measured on 18 May 1995 at Sutton Bonington.

	N0	GAI 3	GAI 5	Ncf	SED (6 df)
Fertile Shoots m^{-2}	419	508	533	523	33.5
Infertile Shoots m^{-2}	33	13	10	8	6.2
Biomass g m^{-2}	522	606	629	556	51.6

On 18 May there were significantly fewer fertile shoots and more infertile shoots m^{-2} in the N0 crop than in the other three crops ($P = 0.01$), but there were no significant differences in total biomass.

5.2.2 Weather conditions

Figure 5.2 shows the mean daily minimum and maximum temperature (°C), incident radiation (MJ m^{-2}) and hours of sunshine and Figure 4.3 (b) the total monthly rainfall (mm) and the wind speed (km h^{-1}) for the period 1 September 1994 to 31 August 1995. The data show that there were no extreme weather conditions during the year, but the summer was very dry. The beginning of July which was warm and sunny was probably partly responsible for the rapid senescence of the crop canopies.

5.3 YIELD

5.3.1 Grain yields

The yields of grain, chaff and straw obtained from hand harvest and of combined grain are shown in table 5.4.

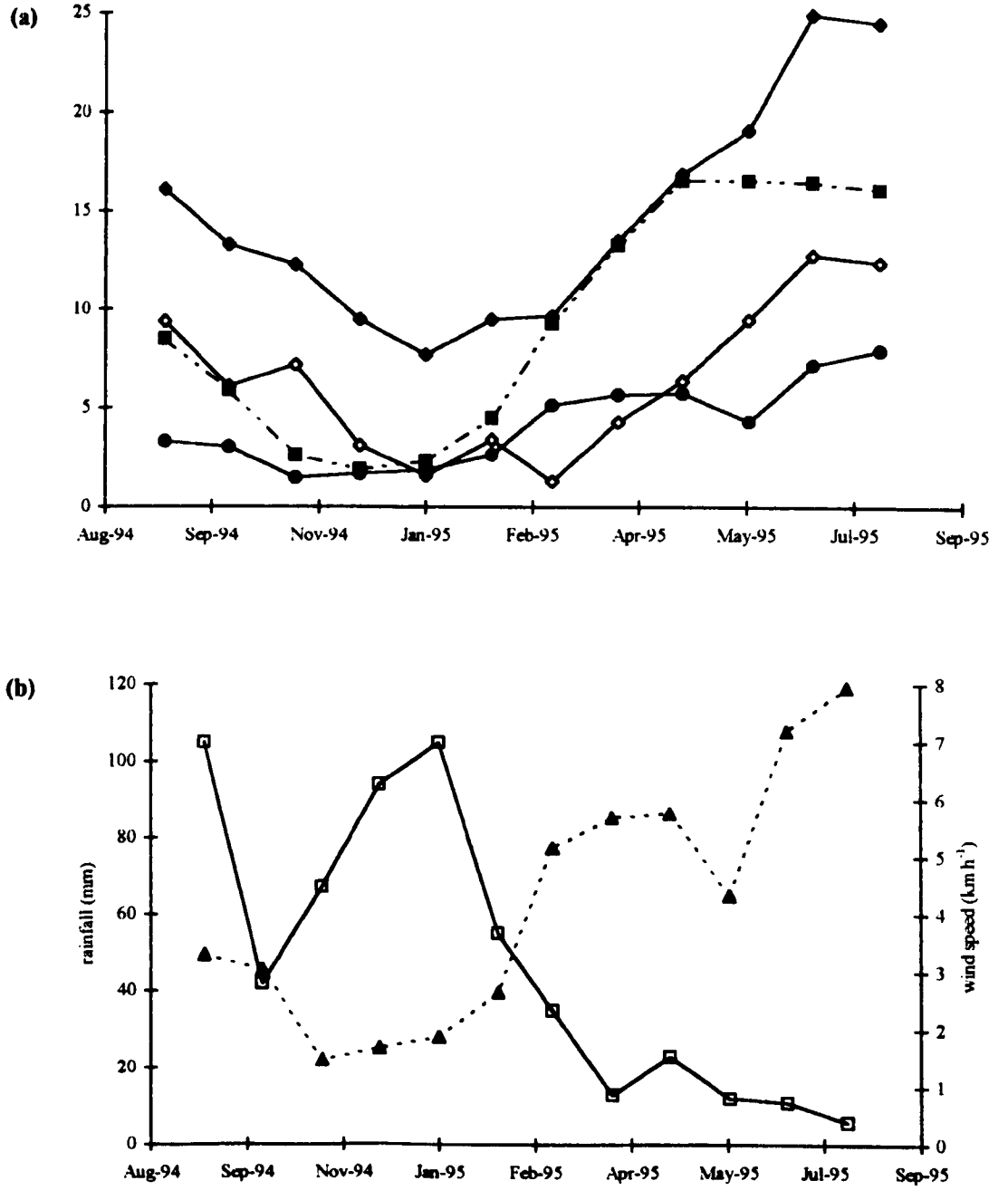


Figure 5.2 (a) mean daily minimum (◊) and maximum temperature, °C (◆), hours of sunshine (●) and incident radiation, MJ m^{-2} (■) and 5.2 (b) total monthly rainfall, mm (□) and wind speed, km h^{-1}(▲) for the period 1 September 1994 to 31 August 1995 at Sutton Bonington.

Table 5.4 Hand harvest components of yield (t ha^{-1}), combine grain yield (t ha^{-1}) and the percentage hand harvest indices of crops grown at Sutton Bonington in 1995.

Treatment	Hand Harvest 100 % DM				85 % DM	Harvest Index			Combine
	Grain	Chaff	Straw	Total	Grain	Grain	Chaff	Straw	85 % DM
N0 - no late-N applied	6.23	1.44	5.90	13.58	7.33	45.9	10.8	43.4	6.41
N0 + 60 kg N ha^{-1} foliar urea	6.21	1.31	5.17	12.68	7.30	48.9	10.3	40.7	7.43
N0 + 60 kg N ha^{-1} prilled ammonium nitrate	4.97	1.10	4.82	10.89	5.85	46.0	10.1	43.9	6.26
GAI 3 - no late-N applied	6.48	1.46	5.95	13.89	7.62	46.7	10.6	42.7	7.74
GAI 3 + 60 kg N ha^{-1} foliar urea	7.05	1.37	5.41	13.83	8.29	49.8	10.2	40.0	7.51
GAI 5 - no late-N applied	7.87	1.65	6.85	16.37	9.26	48.1	10.1	41.8	9.30
GAI 5 + 60 kg N ha^{-1} foliar urea	7.89	1.48	6.83	16.20	9.28	49.0	9.00	41.9	9.08
GAI 5 + 30 kg N ha^{-1} foliar urea on 8 June	7.51	1.57	5.99	15.07	8.83	50.3	10.6	39.0	8.51
GAI 5 + 30 kg N ha^{-1} foliar urea on 20 June	7.33	1.52	5.85	14.95	8.62	49.7	10.5	39.8	8.52
GAI 5 + 30 kg N ha^{-1} foliar urea + Silwet L-77	7.82	1.62	6.30	15.74	9.20	49.6	10.4	40.0	8.62
GAI 5 + 30 kg N ha^{-1} foliar urea + Spray-Fix	7.87	1.60	6.56	16.03	9.26	49.2	10.0	40.7	9.37
Ncf - no late-N applied	8.02	1.76	6.52	16.31	9.44	49.1	10.9	39.9	9.60
Ncf + 60 kg N ha^{-1} foliar urea	7.69	1.72	6.27	15.67	9.04	48.9	11.3	39.8	9.52
SED (24 df)	1.096	0.202	1.134	2.559	1.290	1.560	0.782	1.878	0.642

Grain yields from the hand harvest and combine samples were generally similar but hand harvested yields were more variable and SEDs were large, because of the small amount of crop sampled. The statistical analysis showed no significant effects of the basal or late-N treatments in grain, chaff or straw yields. However the more precise combine yields measured on a larger area of the plot, did show significant treatment effects, ($P = 0.001$). The yield of the N0 crop was significantly smaller than that of the GAI 3 crop and both yielded significantly less than the GAI 5 and Ncf crops. The application of late-N either as foliar urea with or without adjuvants or soil applied ammonium nitrate did not increase combine yields.

5.3.2 Components of yield

There was no significant effect of basal N fertilizer or late-N treatment on the yield of grain, chaff, straw or total biomass of hand harvested samples, with the exception of the N0 crop receiving solid ammonium nitrate which yielded significantly less grain and total biomass than the GAI 5 and Ncf crops.

5.3.3 Percentage harvest index

Percentage harvest indices were not significantly affected by either the basal N or late-N treatment applied. Approximately 50 % of the total biomass was partitioned to the grain, 10 % to the chaff and 40 % to the straw.

5.4 GRAIN QUALITY

5.4.1 Thousand grain weight

The basal N fertilizer treatments did not significantly affect the thousand grain weight (Table 5.5) in either the combine or hand harvested samples, irrespective of the late-N treatment applied.

Table 5.5 Thousand grain weight (g, 85 % DM) of hand harvested and combined grain samples and the % N content of the hand harvested grain from Sutton Bonington 1995.

Treatment	Thousand Grain Weight		% N
	Combine	Hand	Hand
N0 - no late-N applied	44.40	40.28	1.487
N0 + 60 kg N ha^{-1} prilled ammonium nitrate	45.76	42.68	1.790
N0 + 60 kg N ha^{-1} foliar urea	46.96	42.55	1.867
GAI 3 - no late-N applied	45.19	41.72	1.583
GAI 3 + 60 kg N ha^{-1} foliar urea	45.03	42.67	1.827
GAI 5 - no late-N applied	44.97	42.18	1.797
GAI 5 + 60 kg N ha^{-1} foliar urea	44.86	41.68	1.860
GAI 5 + 30 kg N ha^{-1} foliar urea on 8 June	44.23	41.55	1.840
GAI 5 + 30 kg N ha^{-1} foliar urea on 20 June	45.64	42.12	1.830
GAI 5 + 30 kg N ha^{-1} foliar urea + Silwet L-77	44.12	41.88	1.850
GAI 5 + 30 kg N ha^{-1} foliar urea + Spray-Fix	46.17	42.77	1.920
Ncf - no late-N applied	44.96	42.15	2.140
Ncf + 60 kg N ha^{-1} foliar urea	44.88	40.24	2.110
SED (24 df)	0.948	2.607	0.1311

5.4.2 Grain N percentage

The application of basal N fertilizer increased the percentage N content of the grain with the Ncf crop containing significantly more than the other crops (P = 0.01). Only when applied to the N0 crop did late-N increase the percentage N content of the grain.

5.5 N PRESENT IN THE CROP AT HARVEST

The total amount of N taken up by the crop and its distribution was measured on the hand harvested samples (Table 5.6).

The basally fertilized N0, GAI 3, GAI 5 and Ncf crops contained increasing amounts of N at harvest, but statistically only the differences between the N0 and GAI 3 crops compared with the Ncf crop were significant (P =0.01). The applications of late-N either as solid ammonium nitrate or foliar urea with or without adjuvants did not significantly increase the total amount of N taken up by the crops.

A greater amount of N was recovered in the grain of the Ncf crops than from the basally fertilized N0 and GAI 3 crops and there were no significant effects of the late-N treatments. There were no significant effects of any the treatments upon the N content of the chaff or straw.

As a consequence the percentage harvest index for N in the grain was smaller in the N0 crop than in the GAI 3, GAI 5 and Ncf crops, but was not generally affected by the late-N treatments. The exceptions being the GAI 3 crop which received foliar urea and the GAI 5 crop receiving 30 kg N ha^{-1} with Silwet L-77, both had significantly higher N harvest indices than the other late-N treatments.

Table 5.6 The amount of N (kg ha^{-1}) present in the hand harvest components of yield, the total N uptake (kg ha^{-1}) and the percentage N harvest index of the grain, Sutton Bonington 1995.

Treatment	Grain	Chaff	Straw	Total	% N HI
N0 - no late-N applied	94.0	6.7	24.3	125.0	75.6
N0 + 60 kg N ha^{-1} as foliar urea	115.1	6.4	24.9	146.4	78.6
N0 + 60 kg N ha^{-1} as solid ammonium nitrate	88.6	5.0	20.4	114.0	77.9
GAI 3 - no late-N applied	103.4	6.6	25.2	135.2	76.2
GAI 3 + 60 kg N ha^{-1} as foliar urea	131.2	7.1	21.0	159.4	82.9
GAI 5 - no late-N applied	142.6	8.5	32.4	184.5	77.4
GAI 5 + 60 kg N ha^{-1} as foliar urea	147.8	7.6	30.6	186.0	79.6
GAI 5 + 30 kg N ha^{-1} foliar urea on 8 June	140.9	8.2	28.9	178.0	79.2
GAI 5 + 30 kg N ha^{-1} foliar urea on 20 June	137.8	7.9	24.8	170.6	80.9
GAI 5 + 30 kg N ha^{-1} foliar urea + Silwet L-77	146.2	7.6	22.9	176.8	82.3
GAI 5 + 30 kg N ha^{-1} foliar urea + Spray-Fix	151.7	7.1	30.9	189.7	80.2
Ncf - no late-N applied	171.2	8.8	33.0	213.0	80.4
Ncf + 60 kg N ha^{-1} as foliar urea	164.2	8.7	32.5	205.4	79.8
SED (24 df)	27.78	1.311	7.52	35.13	1.913

Table 5.7 The total amount of N fertilizer applied as basal and late-N (kg ha^{-1}), the total N uptake (kg ha^{-1}) and the percentage apparent N recovery by the crops at Sutton Bonington 1995.

Treatment	Basal N Applied	Late-N Applied	Total N Applied	Total N Uptake	% Apparent N Recovery
N0 - no late-N applied	0	0	0	125.0	-
N0 + 60 kg N ha^{-1} as foliar urea	0	60	60	146.4	35.7
N0 + 60 kg N ha^{-1} as solid ammonium nitrate	0	60	60	114.0	-18.3
GAI 3 - no late-N applied	30	0	30	135.2	34.0
GAI 3 + 60 kg N ha^{-1} as foliar urea	30	60	90	159.4	38.6
GAI 5 - no late-N applied	120	0	120	184.5	49.6
GAI 5 + 60 kg N ha^{-1} as foliar urea	120	60	180	186.0	33.9
GAI 5 + 30 kg N ha^{-1} foliar urea on 8 June	120	30	150	178.0	35.3
GAI 5 + 30 kg N ha^{-1} foliar urea on 20 June	120	30	150	170.6	30.4
GAI 5 + 30 kg N ha^{-1} foliar urea + Silwet L-77	120	30	150	176.8	34.5
GAI 5 + 30 kg N ha^{-1} foliar urea + Spray-Fix	120	30	150	189.7	43.1
Ncf - no late-N applied	175	0	175	213.0	50.3
Ncf + 60 kg N ha^{-1} as foliar urea	175	60	235	205.4	34.2
SED (24 df)	-	-	-	35.13	32.17

Table 5.8 The amount (kg ha^{-1}) and the percentage of late-N recovered in the grain and in the whole plant measured at harvest at Sutton Bonington in 1995.

Treatment	N Recovered in the grain (kg ha^{-1})	% N Recovered in the grain	Total N Recovered (kg ha^{-1})	% Total N Recovered
N0 + 60 kg N ha^{-1} foliar urea	21.1	35.2	21.4	35.6
N0 + 60 kg N ha^{-1} prilled ammonium nitrate	-	-	-	-
GAI 3 + 60 kg N ha^{-1} foliar urea	27.8	46.3	24.2	40.3
GAI 5 + 60 kg N ha^{-1} foliar urea	5.2	8.6	2.5	4.16
GAI 5 + 30 kg N ha^{-1} foliar urea on 8 June	-	-	-	-
GAI 5 + 30 kg N ha^{-1} foliar urea on 20 June	-	-	-	-
GAI 5 + 30 kg N ha^{-1} foliar urea + Silwet L-77	3.6	12.0	-	-
GAI 5 + 30 kg N ha^{-1} foliar urea + Spray-Fix	9.1	30.3	5.2	8.6
Ncf + 60 kg N ha^{-1} foliar urea	-	-	-	-

5.5.1 **Percentage apparent N recovery**

The percentage apparent N recovery of the crops was calculated as the total amount present in the crop at harvest minus the amount present in the N0 crop divided by the total amount of N fertilizer applied and is shown in table 5.7. There were no significant differences in the apparent N recovery of any of the basal N crops and this was unaffected by the application of the late-N treatments. All the values for apparent N recovery were very small.

5.5.2 **Recovery of late-N**

Table 5.8 shows the percentage recovery and the amount (kg N ha^{-1}) of late-N as foliar urea recovered from applications made to N0, GAI 5 and Ncf crops. This was calculated as the difference in the total N content and the N content of the grain of the basal N crops that did not receive late-N and the corresponding crops that did. An ANOVA could not be performed on this data as the original unanalyzed data was not available for calculation, therefore the data presented were calculated from the mean values of the grain and total N content of the crops. Where there are values missing, the N content of the basal N crop that did not receive late-N was greater than that of the corresponding crop that did. The data are very variable and suggest that only a small proportion of the applied late-N was recovered by the crop at harvest.

5.6 DISCUSSION AND CONCLUSIONS

5.6.1 **Prolongation of green area**

Maximum GAI was reached between 18 May (flag leaf emergence) and 20 June (during anthesis), probably around ear emergence. Only the application of foliar urea at anthesis to the N0 and Ncf crops prolonged the duration of GAI when measured on 17 July 1995. Soil applied ammonium nitrate did not cause a significant prolongation of GAI as it was

applied to dry soil in which there was insufficient moisture to allow uptake. Foliar urea applied to the GAI 3 and GAI 5 crops did not significantly prolong green area or increase grain yields and this was also reflected in the partitioning of biomass to the grain and the thousand grain weight.

5.6.2 Grain yield and quality

All the foliar urea applications were made as split applications on 20 and 27 June, between mid to late anthesis, this was quite late because by this time the leaf cuticle would have thickened reducing potential N uptake. The N contents of both the grain and the whole crop after the application of late-N were not significantly greater than in the basal N treatments that did not receive late-N, irrespective of the amount of N applied (30 or 60 kg N ha^{-1}), whether foliar urea was applied with the adjuvants Spray-Fix and Silwet L-77, or the N status of the canopy. There was no great benefit either from an earlier application of foliar urea, 30 kg N ha^{-1} applied to a GAI 5 crop on 8 June and 20 June (early and late anthesis respectively). The variability in this experiment was, however, quite large. The combine grain yields showed a response to the basal N treatments applied but not to the late-N treatments. The application of progressively larger amounts of basal N fertilizer increased yield but there were no significant differences between the GAI 5 and Ncf crops irrespective of whether late-N was applied, or how it was applied.

5.6.3 N uptake

The similarity between GAI 5 and Ncf crops suggests that it was not simply the amount of fertilizer N applied but the total amount of N available to the crop including the amount present in the soil, that determined yield. A total of 82 kg N ha^{-1} was present in the soil and crop immediately before the application of spring N fertilizer which represented a large proportion of that present at harvest. Any differences caused by N application may have been obscured by the large amount of N present in the soil as similar amounts of N were recovered by all the crops. However, when small amounts of N fertilizer were applied to

the GAI 3 crops, a slightly greater proportion was recovered by the crop, suggesting that only the amount of N required to supplement the N already available to it was taken up. The large residual N content in the soil also masked any differences between the effectiveness of the late-N treatments in prolonging the duration of canopy GAI and also any differences in the percentage recovery of late-N. Although N was probably not a limiting factor, the GAI of the GAI 3, GAI 5 and Ncf crops was not as large as might have been expected and this may have been related to poor light interception which was not measured as part of this experiment or an insufficient number of shoots m^{-2} to contribute to GAI.

The results from this experiment are not conclusive because of the large experimental errors. However, they do show that on soils with a large residual N content in the spring, applications of N fertilizer can be reduced without a large yield penalty.

Chapter 6: THE DEPOSITION AND UPTAKE OF N FROM APPLICATIONS OF FOLIAR UREA IN THE FIELD

6.1 MATERIALS AND METHODS

Several methods for quantifying the amount of urea present on the surface of the crop were tested. These were, to remove the urea from the surface of the plant material by washing in water or another liquid, measuring the change in the tissue N content of the plant material after foliar urea had been applied and the use of N^{15} labelled urea.

A review of the literature revealed that the most commonly used method was to remove urea by washing the plant material in distilled water. This method had been employed by Cook and Boynton (1952) on apple leaves, and Klein and Weinbaum (1985) and Klein and Zilkah (1986) on almond, olive, avocado and apple leaves and recovered up to 95 % of the applied N when a 0.1 % solution of the surfactants Triton X-100 and L-77 were used. Measuring the change in tissue N was more variable, but was used by Weseley, *et al.* (1985) to support results obtained from washing techniques.

N^{15} labelled foliar urea has been used extensively on many plant species including soyabeans (Morris and Weaver, 1983) and sugar beet (Beringer and Koch, 1985). Bowman and Paul (1989, 1990 a) tested leaf washing, tissue N analysis and N^{15} on tall fescue (*Festuca arundinacea*) and creeping bent grass (*Agrostis stolonifera* L.) turf. They concluded that the tissue N method lacked sensitivity because of the large variability and lack of repeatability. Similar estimates of urea uptake were obtained from leaf washing techniques and N^{15} analysis.

6.1.1 **Leaf washing techniques**

An approach was tested which removed urea from the leaf surface by washing and the urea present in solution determined. A number of different solutions were tested, including solutions of 1:1 ethanol or methanol and water, (P.J. Holloway, personal communication) and the agricultural adjuvants Vassgro Spreader (Vass) and Citowett (BASF), both non-

ionic wetters and spreaders. All were found to interfere with the subsequent chemical analysis of urea but a 0.1 % solution of Triton X-100 (Sigma), a non-ionic wetter, was found to be compatible.

A volume of 200 ml of 0.1 % Triton X-100 was found to be large enough to remove the urea from the surface of groups of leaves or from individual leaves and the urea was easily detected in this volume of solution. Screw cap wide necked plastic bottles with a capacity of 250 ml were found to accommodate the plant material and allowed adequate space for the material to be thoroughly covered by the solution. Ten minutes was sufficient time for the removal of the urea from the leaf surface, and after the plant material was removed using tweezers the washing solutions were immediately frozen at -20 °C to prevent any enzymic or bacterial degradation.

6.1.2 Stratified canopy measurement of N deposition

After the applications of foliar urea, the crop was sampled and the canopy cut into stratified sections to determine where the urea had been deposited. Ten stems were taken randomly from each plot, cut off at soil level and bulked together. The height of each leaf within the canopy was determined and the leaves removed in order, starting with the flag leaf, by cutting just above the ligule. When present, the ear was also sampled and if only partially emerged, it was incorporated into the top part of the stem. In 1994 at IACR-Rothamsted the stem was cut into 10 cm sections from the base upwards, the fresh weight of each sample of leaves, ears or stem pieces was recorded before being placed in 200 ml of 0.1 % Triton X-100 solution. The bottles were gently inverted to ensure complete coverage of the plant material, which was removed after 10 minutes and the solutions were immediately frozen to preserve them. The area of each plant sample was measured, the dry weight determined and the samples milled and analyzed for total N content. Stratified analyses of the crop were made before foliar urea was applied, immediately after application (0), and at 1, 3, 6, 9, 12, 24, and 48 hours after application. The total N content of the plant samples was only measured on samples taken before foliar urea was applied, and 48 hours afterwards.

This procedure was modified slightly for the measurements taken at IACR-Rothamsted and Sutton Bonington in 1995. In order to avoid the excessive handling of the plant material, each leaf (and when present the ear) was cut off directly into 200 ml of 0.1 % Triton X-100 solution. The upper and lower halves of the stem (divided subjectively by length) were cut into shorter sections and placed in separate washing bottles. All the plant material was subsequently analyzed for total N content. The height of each leaf and ear in the canopy and the length of the stem was measured non-destructively in the remaining existing stand. This complete stratified sample analysis was done immediately after the urea had been applied and 96 hours afterwards. In the intervening time only the flag leaves were sampled, at 4, 8, 24, 48, 72 hours after application of urea.

6.1.3 **Measurement of urea in solution**

The amount of urea present in solution was determined directly using the diacetyl monoxime (DAM) colorimetric assay (Bremner 1982). Diacetyl monoxime (2,3 butanedione oxime) reacts directly with thiosemicarbazide (TSC) and urea under acidic conditions. The chemistry of the reactions is not fully known, however it is thought that urea reacts with DAM to form pyrimidine or triazine derivatives but no explanation for the action of TSC in the assay has been found (Bremner 1982).

The assay has been used by several authors to quantify the amount of urea present in potassium chloride extracts of soil (Bremner and Mulvaney, 1978) and in water samples (Nicholson, 1984; Mulvenna and Savidge, 1992). It has been found to be more sensitive and precise than other colorimetric or enzymic methods of urea determination.

The method used was adapted from that of Mulvaney and Bremner (1979), modified from Douglas and Bremner (1970a and b). The volumes of reagents used were scaled down by a factor of ten to allow the reaction to be carried out in a test tube.

6.1.3.1 *Reagents*

DAM reagent: 2.500 g diacetyl monoxime (Fluka) dissolved in 100 ml of demineralized

water.

TSC reagent: 0.250 g thiosemicarbazide (Fluka) dissolved in 100 ml of demineralized water.

Acid reagent: to 240 ml demineralized water, 10 ml concentrated sulphuric acid (AR Fisons) and 250 ml 85 % w/w phosphoric acid (Aldrich) were added.

Colour reagent: 5 ml DAM reagent, 3 ml TSC reagent and 92 ml acid reagent. This was prepared immediately before use as the solution degraded after 30 minutes.

Stock urea solution 0.1 M urea: 0.6006 g urea (AR Fisons) dissolved in 100 ml of demineralized water or 0.1 % Triton X-100.

Urea standards 100, 200 and 400 μM urea: 0.1, 0.2 or 0.4 ml of stock solution were dissolved in 100 ml of demineralized water or Triton X-100.

The DAM, TSC, acid reagents and urea standards were kept refrigerated and freshly prepared once a week. Three standard solutions of known urea concentration and a blank of 0.1 % Triton X-100 as a control, were included in each set of samples analyzed, to provide a calibration graph for calculation of the amount of urea present in solution.

6.1.3.2 *Procedure*

1. 1 ml of sample solution was placed in a pyrex test tube.
2. 3 ml of colour reagent was added and the contents of the test tube thoroughly mixed. A glass marble was placed over the end of the test tube.
3. The test tubes were incubated at 85 °C ± 1 °C in a water bath for 30 minutes and were then placed in a cold running water bath at 12 - 15 °C for 10 minutes.
4. 1 ml of demineralized water was added to the test tube and the contents gently mixed.
5. The absorbance of the resulting pink solution was read on a Cecil Instruments CE 595 Double Beam UV Spectrophotometer at 527 nm.

If the sample solution proved to be too concentrated and exceeded the range of the assay, a dilution of 1:10 was made: 0.1 ml of sample and 0.9 ml of 0.1 % Triton X-100 and

analyzed as above. All sample solutions were analyzed in duplicate.

6.2 OPTIMISATION OF CONDITIONS FOR THE ANALYSIS OF FOLIAR UREA ON PLANT SURFACES

6.2.1 Sensitivity of diacetyl monoxime assay for urea in solution

The range and sensitivity of the diacetyl monoxime assay was tested using solutions of varying concentrations. Figure 6.1 shows that it was sensitive to a concentration of 1 μM of urea and the end point of the reaction was reached at 520 μM, when the relationship between the concentration of urea in solution and its absorbance ceased to be linear.

6.2.2 Washing technique

The optimisation of the leaf washing technique in terms of the minimum length of time required to remove urea from the surface of plant material and the most effective concentration of Triton X-100 was determined under controlled environment conditions. The experiment consisted of a factorial design of five concentrations of Triton X-100 (0, 0.1, 0.25, 0.5, 1.0 %) with six washing times (1, 10, 30, 60, 90, 120 minutes) and two replicates. The treatments were duplicated on single leaves or artificial targets of strips of acetate. Foliar urea as the equivalent of 15 kg N ha^{-1} in 200 l ha^{-1} of water was applied using a track sprayer (see section 7.2.1.3), delivering 0.326 mg urea cm^{-2}. After spraying, the leaves or acetate strips were washed and the concentration of urea in solution determined. The data for the amount of urea measured as being present on the surface of the acetate strips and the flag leaves are shown in tables 6.1 and 6.2 respectively.

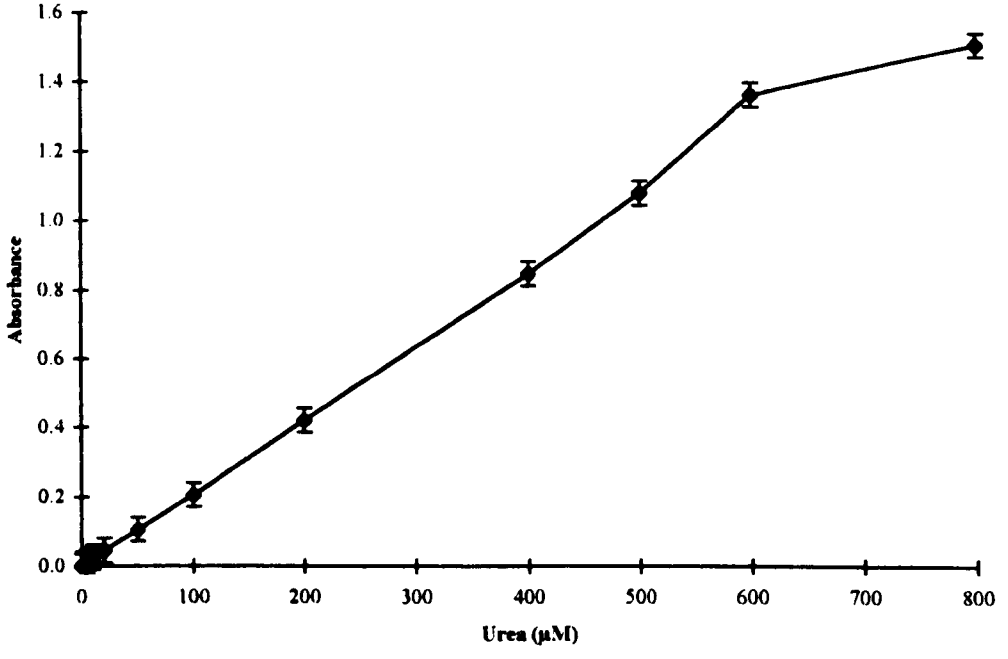


Figure 6.1 The standard graph for the diacetyl monoxime assay for the presence of urea in solution, showing the sensitivity (to 1 μM) and the end point when the relationship between urea concentration and absorbance ceased to be linear (520 μM). The SEDs shown have 24 df.

Table 6.1 Urea (mg cm^{-2}) removed from the surface of acetate strips when washed in a range of concentrations of Triton X-100 for differing lengths of time.

	Concentration of Triton X-100 (%)					
Washing Time (Minutes)	**0**	**0.1**	**0.25**	**0.5**	**1.0**	**Time Means**
1	0.228	0.269	0.254	0.265	0.271	0.257
10	0.225	0.252	0.256	0.242	0.292	0.253
30	0.239	0.266	0.265	0.263	0.261	0.259
60	0.230	0.267	0.261	0.293	0.248	0.260
90	0.233	0.269	0.239	0.249	0.245	0.247
120	0.243	0.277	0.234	0.257	0.249	0.252
Concentration Means	0.233	0.266	0.251	0.261	0.261	0.255*

* Grand Mean

For comparisons between the mean urea recovered from different concentrations of Triton X-100 in solution SED = 0.0079, 4 df, and between the differing lengths of time the acetate strip was washed for SED = 0.0063, 25 df. The interaction between time and concentration SED = 0.0152, 25 df, except when comparing between the same concentrations of Triton X-100 SED = 0.0142, 25 df.

The presence of Triton X-100 in solution significantly increased the amount of urea that was recovered from the surface of the acetate strips ($P = 0.05$) but there were no significant differences in the effectiveness of the different concentrations used. The length of time for which the acetate was washed did not affect the amount of urea recovered in solution, and this was also the case for the flag leaves. Using this data it was decided to wash the leaves for ten minutes in a 0.1 % solution of Triton X-100.

Table 6.2 Urea (mg cm^{-2}) removed from the surface of flag leaves when washed in a range of concentrations of Triton X-100 for differing lengths of time.

	Concentration of Triton X-100 (%)					
Washing Time (Minutes)	**0**	**0.1**	**0.25**	**0.5**	**1.0**	**Time Means**
1	0.137	0.171	0.114	0.210	0.164	0.159
10	0.131	0.141	0.174	0.133	0.157	0.147
30	0.121	0.136	0.153	0.153	0.115	0.135
60	0.140	0.118	0.130	0.182	0.161	0.146
90	0.142	0.127	0.137	0.115	0.168	0.138
120	0.153	0.179	0.103	0.120	0.122	0.135
Concentration Means	0.137	0.146	0.135	0.152	0.148	0.143*

* Grand Mean

For comparisons between the mean urea recovered from different concentrations of Triton X-100 in solution SED = 0.0171, 4 df, between the means of length of time the acetate strip was washed for SED = 0.0107, 25 df. The interaction between time and concentration SED = 0.0277, 20 df, except when comparing between the same concentrations of Triton X-100 SED = 0.0239, 25 df.

Only approximately 75 % of the applied urea was recovered from the surface of the acetate strip and 50 % from the flag leaves. The discrepancy in the amount applied and the amount recovered immediately after application can probably be accounted for by spray drift and evaporation between the sprayer and the leaf surface, it clearly represents a major source of loss of sprayed urea even under controlled conditions. The differences between the deposition onto the acetate and the leaf could be caused by the differences in the surface of the two targets, the acetate reducing the amount lost by bounce off and perhaps also attracting spray droplets.

The amount of urea recovered from the leaf surface was examined in more detail by applying urea to freshly cut flag leaves using a Gilson pipette to ensure that an exactly known amount of urea (30.2 mg) was applied. The urea was then washed from the leaf surface in 200 ml of 0.1 % Triton X-100 for 10 minutes and the amount of urea present in solution determined.

The washing technique measured the urea that was present on the leaf surface reasonably accurately, 27.8 mg (SED = 0.623, 2 df) of urea was measured as present in solution, 92 % of the amount applied.

6.2.3 Preservation of samples

The effect of prolonged storage (four to ten months) at -20 °C, was assessed using solutions of known urea concentration in 0.1 % Triton X-100 solution, frozen for four or ten months. The results are shown in table 6.3; the data are the mean of five replicates. The solutions were defrosted in hot water for 30 minutes before reanalysing their urea concentrations.

Table 6.3 The effects of length of storage as a frozen solution on urea concentration (μM).

Initial Concentration	**Length of Storage**	
	After 4 months	**After 10 months**
99.6	97.6	96.2
399.6	397.6	396.2

SED = 1.061 (20 df) for comparisons between concentration and length of freezing.

There was no significant difference between the initial amounts of urea and those measured after four months freezing, but there was significantly less present after ten months ($P = 0.05$). However, the extent of loss was small and not affected by the initial concentration of urea.

Samples of the solutions used to wash urea from the leaves were usually frozen at -20 °C to prevent any enzymic or bacterial degradation whilst awaiting analysis. Mulvenna and Savidge (1992) found that storage at -20 °C, even for a short period of 6 days resulted in a decrease of 2.0 μg N l^{-1} in the amount of N that was detectable in samples of seawater. However, a sample of seawater would have a much larger enzymic and bacterial activity than the samples of washing solution, which was prepared using demineralized water. The seawater samples also contained a much smaller amount of urea, approximately 15 μg N l^{-1}, considerably less than would be found in the washing samples.

6.2.4 Preparation of samples for analysis

Mulvenna and Savidge (1992) showed that leaving solutions to defrost at room temperature decreased the measured amounts of urea in solution. There were smaller losses from samples defrosted quickly in warm water but the results were more variable. However, this was not a problem that was experienced whilst analysing solutions used to wash leaves. Two solutions of 100 and 400 μM urea were split into three, one part was kept overnight at room temperature and the other two were frozen at -20 °C for a minimum of 16 hours. One of these two samples was then defrosted at room temperature, the other in hot water (approximately 50 °C) for 30 minutes. The concentration of urea in the three solutions was determined.

Table 6.4 The effect of freezing and defrosting conditions on the concentration (μM) of urea in solution.

Initial Concentration	Maintained at Room Temperature	Defrosted at Room Temperature	Defrosted in Hot Water
100	95.8	98.0	98.5
400	394.5	397.8	398.5

SED = 0.683 (15 df) for comparisons between solution concentration and method of defrosting.

Approximately 5 μM of urea degraded during storage at room temperature, the actual amount apparently being independent of the initial urea concentration. Less was lost from frozen samples irrespective of whether they were defrosted at room temperature or in hot water. Frozen solutions were therefore routinely defrosted in warm water before analysis.

6.3 N DEPOSITION AND UPTAKE FROM FOLIAR APPLICATIONS IACR-ROTHAMSTED 1994

The application of 40 kg N ha^{-1} as foliar urea on three occasions during growth, at flag leaf emergence, just prior to ear emergence and during anthesis, to GAI 5 crops allowed the detailed measurement of the deposition of N onto the surface of the crop and its subsequent behaviour and uptake. Of the total N applied to these crops 37 - 53 % was recovered by harvest (Table 3.7). The recovery of the late-N, either foliar or soil applied N, was much more variable, between 32 - 110 % (Table 3.8). The amount of urea deposited onto the canopy was measured by stratified samplings, washing and chemical analytical techniques outlined in section 6.1. Measurements were made only on the early sown crops and only for the first 48 hours following application. The data presented are for the treatments applied at ear emergence and anthesis because the intended samplings following the application at flag leaf emergence were disrupted by heavy rainfall that washed urea from the crop.

6.3.1 **N deposition onto and uptake by the whole crop**

The total amount of N washed from the surface of the GAI 5 crops after an application of 40 kg N ha^{-1} is shown in table 6.5. Approximately 25 % of the applied N was intercepted by the crop after application at ear emergence and 41 % from the anthesis application. The amount deposited onto the soil surface was not measured.

Table 6.5 N (kg ha^{-1}) washed from the surface of a GAI 5 crop at IACR-Rothamsted 1994 from an application of 40 kg N ha^{-1} as foliar urea, initially and then 6 and 48 hours afterwards. N lost was calculated as the difference between the initial amount and that present at 48 hours.

Treatment	N Present on Crop Surface			N Lost
	Initial	6 Hours	48 Hours	
foliar urea at ear emergence	9.71	11.01	6.18	3.53
foliar urea at anthesis	16.30	17.32	3.35	12.95

SED = 2.666, 10 df for comparisons between N present at each time period and SED = 1.608, 10 df for comparisons of the amount of N lost in total.

The actual amount of N present on the crop initially may have been masked by the handling of the wet crop material resulting in some of the N being removed, so it was not possible to determine either the exact amount of urea that was deposited onto the crop or the amount lost from the surface over 48 hours. The point when the foliar urea would have dried onto the leaf surface (and the handling of the plant material would have removed only a minimal amount of N) was determined as six hours after application from visual observations of the time taken for the urea to dry on the leaf surface. At this time more urea was present on the crop but not a significantly greater amount than was present initially. Even though the means were very different, there was no significant difference in the amount of N present initially on the two crops at ear emergence or anthesis. The differences in the amount present at 6 hours and remaining at 48 hours after the application of foliar urea at ear emergence, were only just non-significant. Only the anthesis application resulted in a significantly smaller amount of N being present on the crop after 48 hours than was present initially. These highly variable data can therefore only be used to state that N was deposited onto the crop and some was then subsequently lost from the surface of the crop.

During the 48 hours after each application of foliar urea there was a small amount of rain, in each case on the day following the application, but the maximum rainfall was only 1.5 mm. The application of foliar urea made during anthesis was applied in warmer, sunnier

conditions than that applied at ear emergence. The maximum temperature was 25.3 °C with 14.2 hours sunshine at anthesis compared to 14.9 °C and 8.0 hours of sunshine at ear emergence.

The application of foliar urea at ear emergence and anthesis did not result in a significant increase in the N content of the crop over a 48 hour period. But of the 40 kg N ha^{-1} applied, only 44 % at ear emergence and 25 % at anthesis was present in the crop 48 hours after application. These figures suggest that for foliar urea applied at ear emergence, the amount of N deposited onto the leaf surface initially was greatly under estimated.

6.3.2 Penetration of N into the canopy

The amount of N deposited onto each leaf layer initially and six hours after application and the amount remaining 48 hours later are shown in Figures 6.2 (a and b) for foliar urea applied at ear emergence and anthesis respectively. A leaf layer consisted of the leaf itself and the stem above it. The majority of the N was deposited onto the flag leaf, approximately 50 % of the total intercepted, significantly more than any other organ ($P = 0.001$ SED = 0.631, 16 df). When present, approximately 20 % of the total was deposited on the ear, the same as for the leaf below the flag leaf, flag -1. The lower leaves and the base of the stem accounted for the remainder, with only about 10 % of the total N deposited penetrating below flag -1. This pattern of deposition was not significantly affected by the growth stage of the crop to which foliar urea was applied or by the size of the crop measured as GAI; at ear emergence the early and late sown crops had GAIs of 2.4 and 3.7 respectively and 2.0 and 3.0 respectively at anthesis.

There were no significant differences in the amount of N present on each of the leaf layers between the initial sample and the sample taken 6 hours afterwards for both applications. However, at anthesis significantly less N was present on each of the leaf layers 48 hours

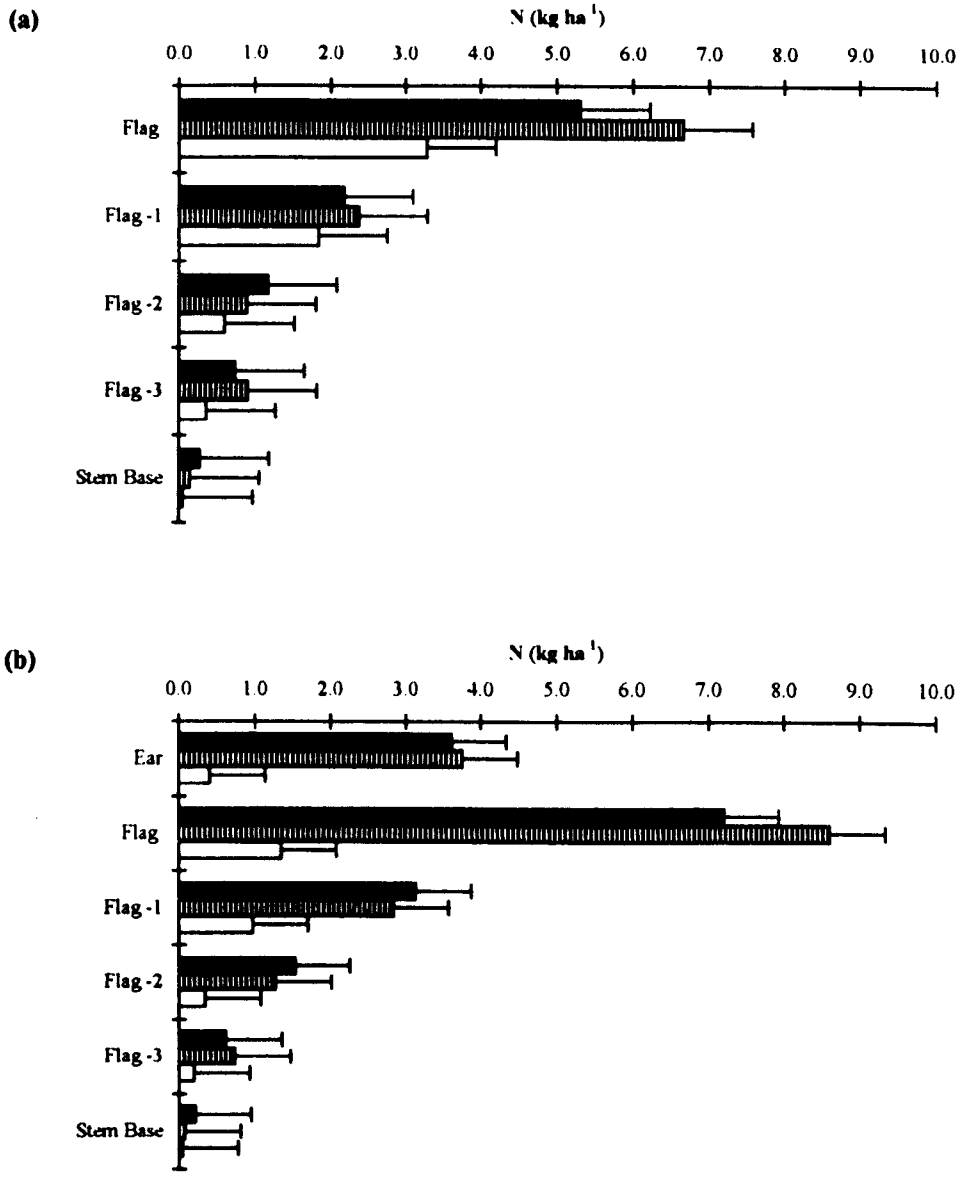


Figure 6.2 The amount of N deposited onto the stratified layers of a GAI 5 crop immediately (black bars), 6 hours (vertical lined bars) and 48 hours (open bars) after the application of 40 kg N ha^{-1} as foliar urea at ear emergence (a) and anthesis (b). The SEDs shown are for comparisons between the amount of N present on the different leaves at each time and have 34 df.

after application of foliar urea than was present initially or 6 hours afterwards, but at ear emergence there was no significant decline over this period.

6.4 N DEPOSITION AND UPTAKE FROM FOLIAR APPLICATIONS IACR-ROTHAMSTED 1995

The spatial deposition and dynamics of uptake of foliar N were studied in N0, GAI 5 and Ncf crops at anthesis and the effects of rate, timing and the use of adjuvants in GAI 5 crops. The amounts of N deposited on and within the crop were determined by washing urea from the leaves, stems and ears of stratified sections of the crop at different times after application. The actual N uptake was measured by determining the N content of the dried plant material.

Applications of foliar urea were made at flag leaf emergence, ear emergence and anthesis and were applied under weather conditions that were not markedly different at time of application, or during the period of measurement that followed application. Maximum temperatures were quite warm, ranging between 13.0 and 19.4 °C and the lowest minimum temperature was 5.8 °C. The number of hours of sunshine was quite variable with the longest period of 10.1 hours, however there was mostly 2 to 3 hours of sunshine per day. Wind speed was also quite variable but did not exceed the recommended maximum for spraying. Heavy rain was only recorded on two days, 3 and 4 June (during measurements made after applications at 'ear emergence'), when 13.6 and 12.6 mm were recorded respectively. Small amounts, less than 3 mm, fell on other rain days.

6.4.1 **N deposition onto the whole crop**

The total amount of N intercepted by the crop canopies was significantly affected by canopy size, the amount of N applied and the use of adjuvants ($P = 0.001$), but not by the timing of application. It should be noted that the ear had not emerged when the 'ear emergence' applications of foliar urea were applied. Table 6.6 shows the total amount of N that was intercepted and expressed as a percentage of the N applied.

Table 6.6 The amount of N deposited (kg ha^{-1}) onto the crop canopies immediately after the application of foliar urea and expressed as a percentage of the amount of N applied, the amount remaining 96 hours afterwards (kg ha^{-1}) and expressed as a percentage of the amount of N applied; and the amount of N lost from the surface of the crop over that period (kg ha^{-1}) at IACR-Rothamsted 1995.

Treatment	N Deposited 0 Hours	% Deposited	N Remaining 96 Hours	% Remaining	N Lost 0-96 Hours
N0 + 30 kg N ha^{-1} at anthesis	7.94	26.4	2.67	8.90	5.27
GAI 5 + 30 kg N ha^{-1} at ear emergence	18.81	62.7	2.01	6.70	16.80
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	11.03	36.7	1.21	4.03	9.82
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	17.36	57.8	1.54	5.12	15.82
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	13.01	43.3	1.74	5.79	11.27
GAI 5 + 30 kg N ha^{-1} at anthesis	19.35	64.5	1.28	4.26	18.07
GAI 5 + 60 kg N ha^{-1} at anthesis	30.98	51.7	3.26	5.43	27.72
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	11.13	37.1	1.95	6.50	9.18
Ncf + 30 kg N ha^{-1} at anthesis	10.76	37.1	2.79	9.31	7.97
SED (16 df)	2.947	8.89	0.3995	1.193	2.859

For comparison between the amount of N present at 0 and 96 Hours SED = 2.183 (34 df).

A significantly smaller amount of N was deposited onto the surfaces of the N0 and Ncf crops, between which there were no significant differences, than onto the GAI 5 crops at anthesis. Although there was no significant difference in measured GAI between the GAI 5 and Ncf crops there was a subtle difference in canopy architecture, with the Ncf crop (407 shoots m^{-2}) providing a denser upper layer of slightly, but not significantly larger flag leaves, which may have reduced penetration into the crop and encouraged bounce off from the leaf surface. The GAI 5 crop (406 shoots m^{-2}) was more open with more vertically orientated leaves despite having a similar number of shoots m^{-2}. The N0 crop (297 shoots m^{-2}) had greater space between the shoots allowing increased penetration onto the soil surface.

The timing of application of foliar urea to a GAI 5 crop did not significantly affect the amount of N that was deposited onto the crop and this was also true when Silwet L-77 was applied with the foliar urea, although a significantly smaller amount of N was deposited. The sticker Spray-Fix was the only adjuvant that did not have a detrimental effect upon the amount of N deposited onto the surface of a GAI 5 crop, significantly less N was deposited when Silwet L-77 (a spreader) was applied with the foliar urea at ear emergence compared to when an adjuvant was not used. A significantly greater amount of N was deposited onto a GAI 5 crop when 60 kg N ha^{-1} was applied at anthesis (P = 0.01), although when expressed as a percentage of the amount applied, there was not a significant increase in the proportion deposited.

6.4.2 Loss from the whole crop

The total amount of N (kg ha^{-1}), the percentage of the amount applied remaining on the surface of the crop 96 hours after application of foliar urea and the amount of N lost from the crop surface, are shown in Table 6.6. The terms 'loss' and 'lost' are used to describe the decline in the measured amount of N present on the surface of the crop and not uptake.

Significantly more N remained on the surface of the N0 and Ncf crops, between which there were no significant differences, 96 hours after the application of foliar urea at anthesis,

than was present on the GAI 5 crops which also received late-N ($P = 0.001$). Both the N0 and Ncf crops recorded a significantly smaller loss of N than from the corresponding GAI 5 crop. The application of foliar urea at ear emergence did not significantly differ in either the amount of N lost from the crop surface or the amount of N remaining on it compared to applications at anthesis. There was also no effect of timing of application of foliar urea when applied with the spreader Silwet L-77. There were no significant differences in the amount remaining on the crop after 96 hours but a significantly smaller amount of N was lost from the crop surface, compared to when an adjuvant was not applied. The application of foliar urea with Spray-Fix and LI-700 did not have a significant effect upon either the amount remaining at 96 hours or the amount lost from the crop surface over this time compared to when an adjuvant was not used. The application of 60 kg N ha^{-1} at anthesis resulted in a significantly greater amount of N remaining on the crop and a significantly greater amount lost from it compared to when only 30 kg N ha^{-1} was applied ($P = 0.001$). However when expressed as a percentage of the amount applied there was no significant difference.

6.4.3 N uptake by the whole crop

N uptake was measured over 96 hours by change in tissue N content and is shown in Table 6.7. The N contents shown are of plant material which had had any urea present on the surface washed off. There were no significant differences in the amount of N taken up irrespective of the foliar urea treatment applied or the basal N status of the crop to which it was applied. Although the initial N content of the GAI 5 crops prior to the application of foliar urea was variable (134 to 177 kg N ha^{-1}) this did not affect the amount of N that was taken up following applications of foliar urea.

In theory it may have been possible to estimate the actual loss of N from the plant system, by subtracting the value for uptake of N over 96 hours (Table 6.7, 'effect of foliar urea') from the measured loss of N from the leaf surface over the same period (Table 6.6). Although this would be a logical calculation to make in order to estimate the loss by

volatilization, given the variability of the data for N uptake and the lack of significance it would be unwise to make any further assumptions from these data.

Tables 6.7 Total N content (kg ha^{-1}) just before and 96 hours after the application of late-N as foliar urea at IACR-Rothamsted in 1995.

Treatment	N Content		Effect of foliar urea
	0 Hours	96 Hours	
N0 + 30 kg N ha^{-1} at anthesis	44.9	47.4	2.5
GAI 5 + 30 kg N ha^{-1} at ear emergence	134.1	141.2	7.1
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	176.9	172.2	-4.7
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	173.5	175.4	1.9
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	158.9	172.5	13.6
GAI 5 + 30 kg N ha^{-1} at anthesis	154.2	159.2	5.0
GAI 5 + 60 kg N ha^{-1} at anthesis	135.8	154.7	18.9
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	144.1	156.1	12.0
Ncf + 30 kg N ha^{-1} at anthesis	200.5	212.1	11.6
SED (16 df)	11.88	11.92	12.67

SED = 11.69, 34 df, for comparisons between the N content at 0 and 96 hours within the same treatment.

6.4.4 N deposition onto stratified layers and penetration into the canopy

After the application of late-N as foliar urea the canopy was cut into stratified leaf layers with the amount of N present on the stem above a leaf being incorporated into the value for

that leaf. The pattern of deposition of N (kg ha^{-1}) onto the stratified layers of the N0, GAI 5 and Ncf crops at anthesis after the application of foliar urea are shown in figures 6.3 (a-c). The amount of N deposited onto the surface of each of the leaf layers decreased with increasing depth into the canopy. The flag leaf was the most important organ for N deposition, up to 30 % of the total amount of N deposited was deposited onto it. As in 1994, the top half of the canopy (ear to flag -1) of both the N0 and Ncf crops was responsible for over 60 % of the total amount of N intercepted by the crop and the pattern of deposition onto the flag leaf, flag -1 and the ear were essentially the same for both crops with each organ responsible for approximately 25, 20 and 20 % of the total deposited respectively. However, foliar urea applied to a GAI 5 crop at anthesis produced a different pattern of deposition. The actual amounts of N (kg ha^{-1}) present on each leaf layer were significantly greater than for the corresponding leaves of the N0 and Ncf crops and there was significantly less N present on the ear ($P = 0.001$). A maximum value of 30 % of the total amount of N deposited was present on the flag leaf, 25 % on flag -1 and 12 % on the ear.

The application of foliar urea just prior to ear emergence to a GAI 5 crop Figure 6.3 (d), did not significantly affect the amount of N deposited onto any of the stratified leaf layers compared to when foliar urea was applied at anthesis. Similarly, the flag leaf intercepted 30 % and flag -1 25 % of the applied N deposited. When Silwet L-77 a spreader, was applied with the foliar urea the pattern of N deposition was subtly altered with flag -1 having the most N deposited onto it, 33 % of the total and 20 % was deposited onto the flag leaf. This was not significantly affected by the timing of application or the presence of the fully emerged ear at anthesis which received 20 % of the total N deposited, (figure 6.3 (e) and (f)). Figures 6.3 (g) and (h) illustrate the pattern of deposition obtained when foliar urea was applied with the sticker Spray-Fix and the penetrant LI-700, which were essentially the same despite significantly more N being deposited in total when Spray-Fix was applied. A larger amount of N was present on flag -1 (30 %) than on the flag leaf (24 %), although the differences were not significant. The penetration of N to the lower leaves within the canopy was not significantly affected by the addition of any of the adjuvants.

Although the total amount and the amounts present on the stratified leaf layers of the GAI 5 crop that received 60 kg N ha^{-1} as foliar urea at anthesis were significantly greater than when 30 kg N ha^{-1} was applied, there were no significant differences in the percentage of the total deposited that was present on each leaf layer or the pattern of deposition (figure 6.3(i)). 25 % of the total deposited was present on the flag leaf, 23 % on flag -1 and 20 % on the ear and only these values were significantly greater than when half the amount of N was applied.

6.4.5 Loss of N from the surface of stratified layers

A significant amount of N was lost from each of the leaves ($P = 0.001$), Again 'loss' here is a combination of N uptake by the leaf and true loss by volatilization. The greatest amount (kg ha^{-1}) was lost from the flag leaf, significantly more than from any other organ except flag-1. These two organs together were responsible for approximately 50 % of the total N lost in all the foliar urea treatments and irrespective of the basal N crop to which it was applied. However, where the initial deposition of N onto the leaves was low, particularly in the N0 and Ncf crops (figure 6.3 (a) and (b)), the amount of N lost from the crop surface was correspondingly small, in proportion to the amount of N present initially and therefore in these two crops the amount of N remaining on the surface was larger than the amount on the GAI 5 crop (figure 6.3 (c)).

The timing of application of late-N as foliar urea to a GAI 5 crop either at ear emergence or anthesis (figure 6.3 (c) and (d)), did not significantly affect either the amount of N remaining on the surface of the layers at 96 hours or the amount lost over that period and this was also true for foliar urea applications that included Silwet L-77 (figure 6.3 (e) and (f)). However when this adjuvant was applied a significantly greater amount of N remained on the flag leaves and significantly less was lost from the stratified layers. Spray-Fix was the only adjuvant applied that resulted in a similar amount of N deposited and remaining on the leaf layers after 96 hours compared to when foliar urea was applied on its own (figure 6.3 (g)). Foliar urea applied with LI-700 behaved in a similar way to when Silwet L-77

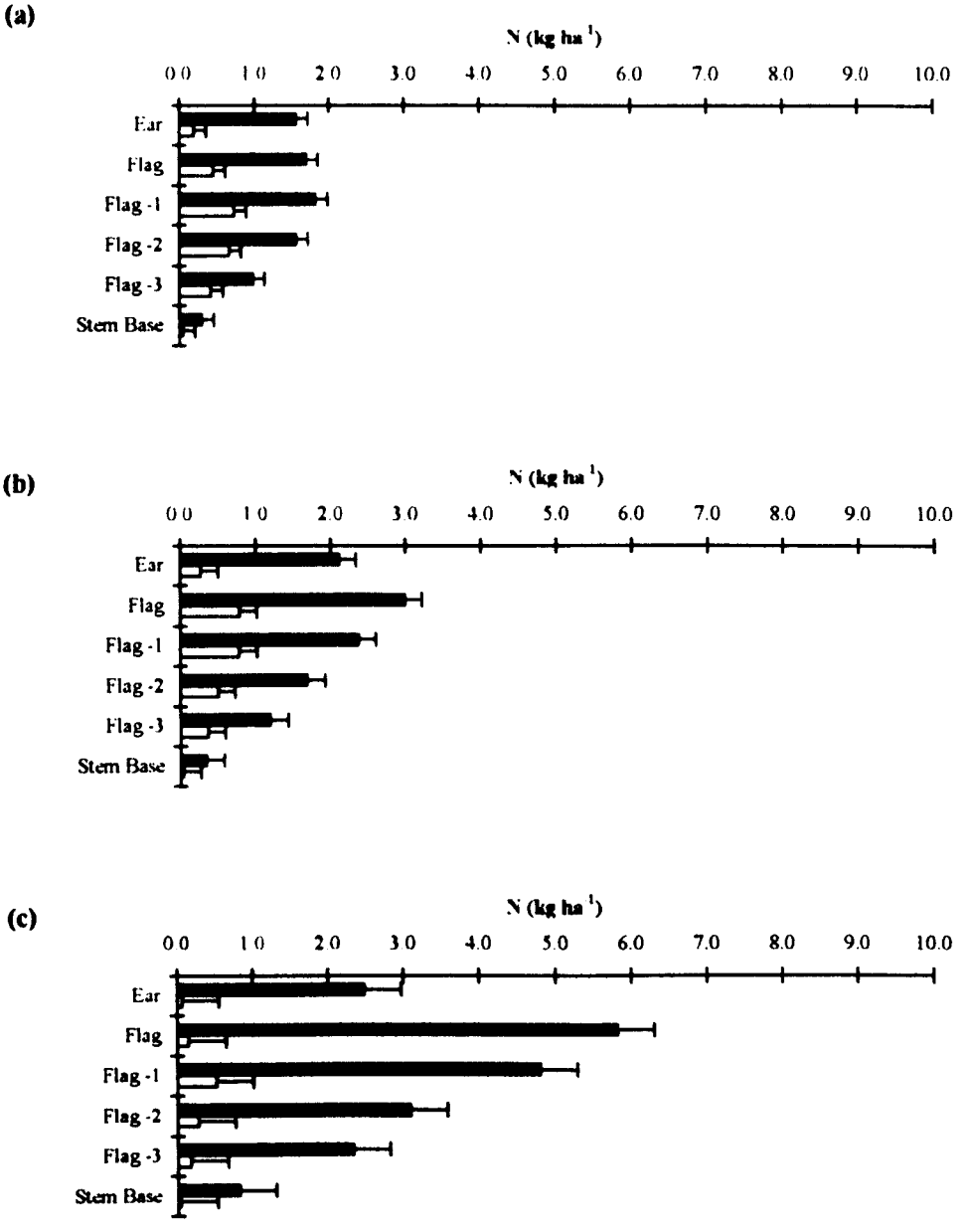


Figure 6.3 The deposition of N (kg ha^{-1}) onto stratified leaf layers of (a) N0, (b) Ncf and (c) GAI 5 crops from applications of 30 kg N ha^{-1} as foliar urea made during anthesis at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount remaining 96 hours afterwards. The SEDs shown have 22 df and are for comparisons between both time and leaf layer.

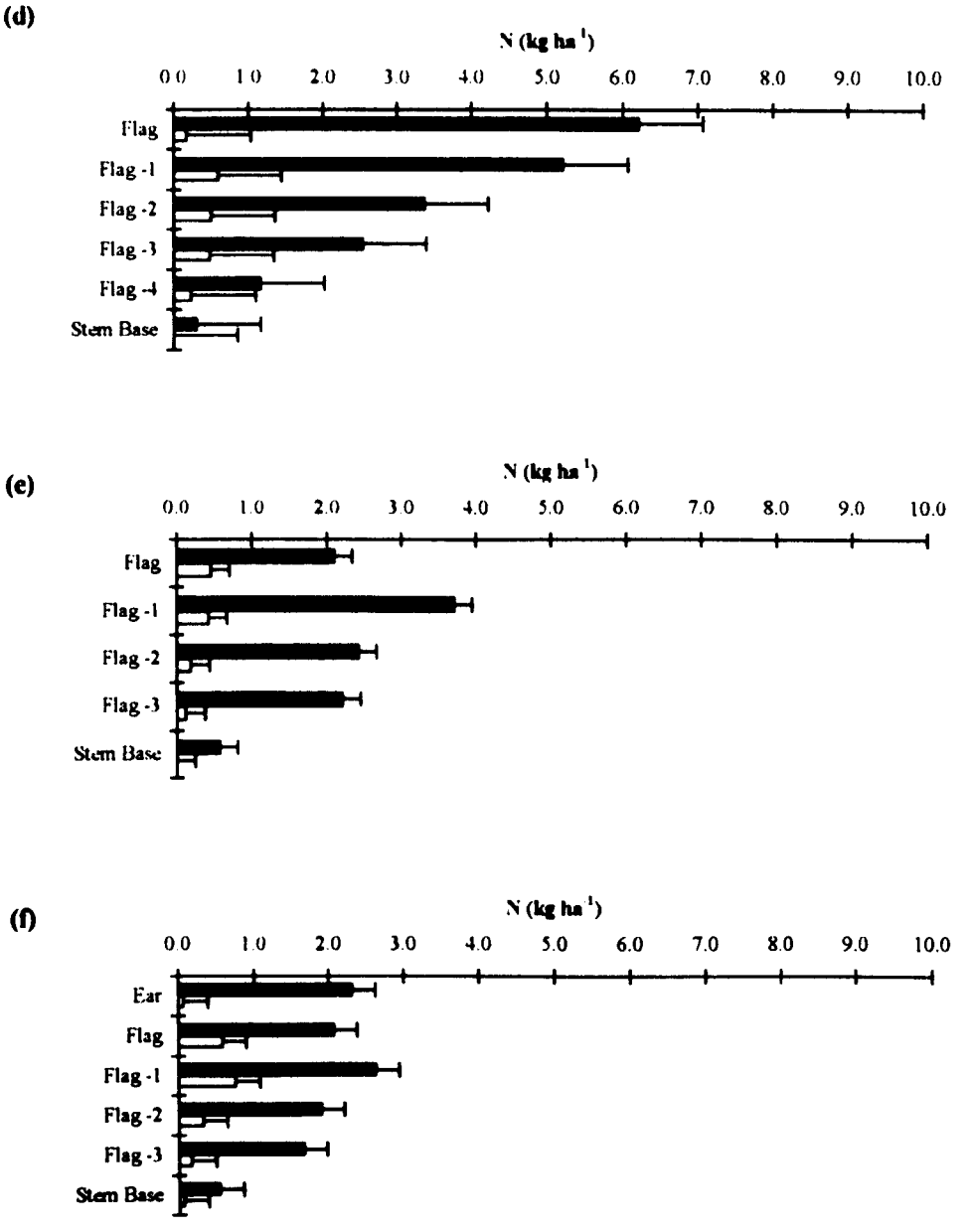


Figure 6.3 The deposition of N (kg ha^{-1}) onto stratified leaf layers of GAI 5 crops receiving (d) 30 kg N ha^{-1} at ear emergence, (e) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at ear emergence, (f) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at anthesis as foliar urea at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount remaining 96 hours afterwards. The SEDs shown have 18 df (22 df for applications made at anthesis) and are for comparisons between both time and leaf layer.

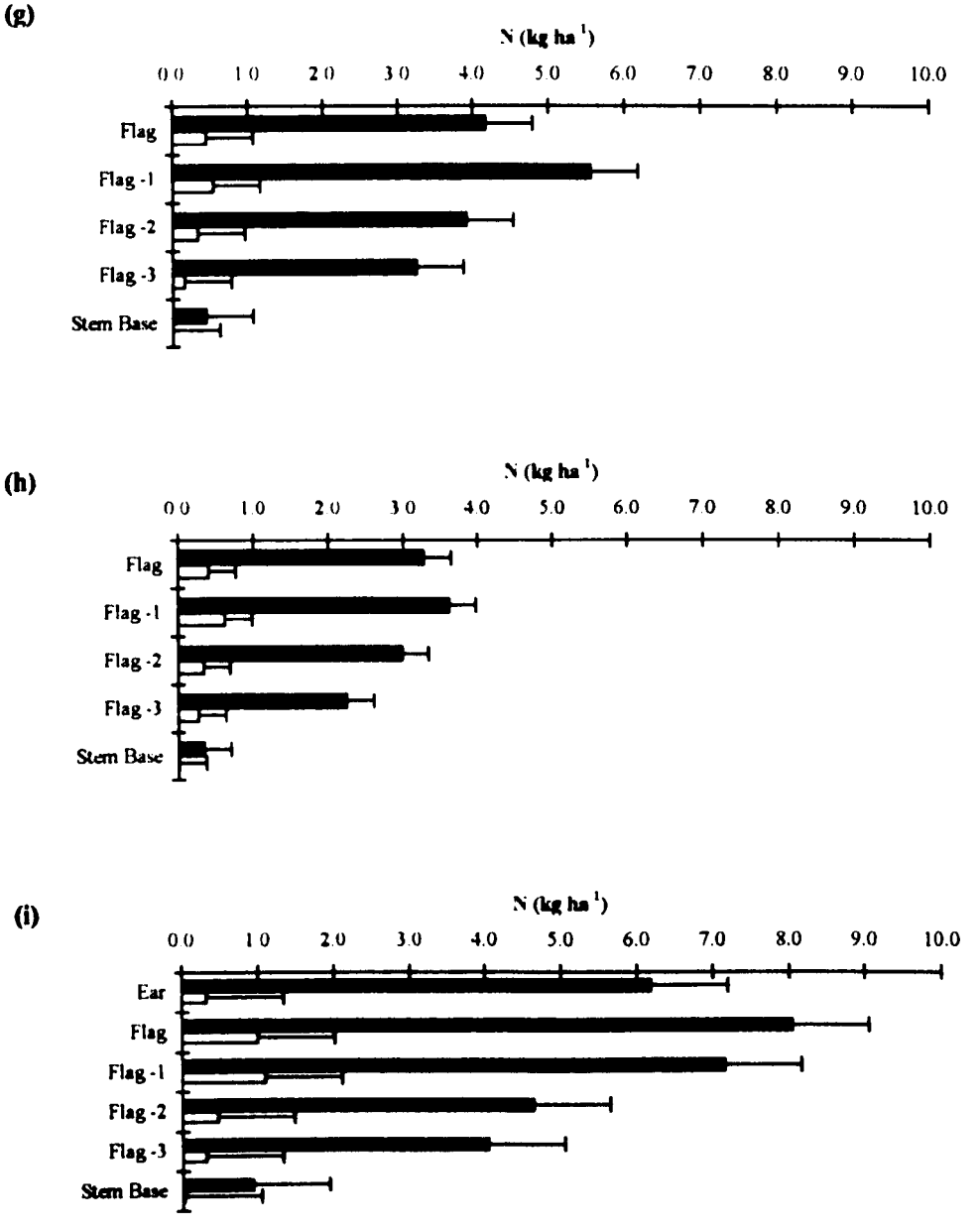


Figure 6.3 The deposition of N (kg ha^{-1}) onto stratified leaf layers of GAI 5 crops receiving (g) 30 kg N ha^{-1} with 0.1 % Spray-Fix at ear emergence, (h) 30 kg N ha^{-1} with 0.1 % LI-700 at ear emergence, (i) 60 kg N ha^{-1} at anthesis as foliar urea at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount remaining 96 hours afterwards. The SEDs shown have 18 df (22 df for applications made at anthesis) and are for comparisons between both time and leaf layer.

was applied (figure 6.3 (h)) with only a small amount of N lost and more N remaining on the flag leaf. After the application of 60 kg N ha^{-1} (figure 6.3 (i)) a significantly greater amount of N was lost than from any other treatment, the amount remaining at 96 hours was also significantly higher, corresponding with the amounts of N deposited.

6.4.6 N uptake by stratified layers

There were no significant changes in the N concentration in any of the plant parts after the application of foliar urea when measured over a 96 hour period. Both initially and after 96 hours the N0 crop contained a significantly smaller, and the Ncf crop a significantly higher percentage of N than the GAI 5 crops ($P = 0.001$) and there were no significant differences between these last two crops. The flag leaf contained a significantly greater concentration of N than the other plant parts including the ear. The stem base contained the smallest concentration of N.

Figure 6.4 (a) illustrates the distribution of N (kg ha^{-1}) in the N0 crop immediately after the application of foliar urea and 96 hours afterwards. Unlike the GAI 5 and Ncf crops there were no significant differences in the N content of each of the leaves and none of them showed a significant change over 96 hours. Only the ear, which contained significantly more N than the other plant parts ($P = 0.001$), showed a significant increase in N content 96 hours after application ($P = 0.001$). As with the N0 crop the greatest proportion of the N was present in the ear of the Ncf crop, (figure 6.4 (b)) and only the ear and the top and bottom halves of the stem showed a significant increase 96 hours after the application of foliar urea at anthesis.

The distribution of N present in a GAI 5 crop that received 30 kg N ha^{-1} as foliar urea at anthesis is shown in figure 6.4 (c). The ear contained a significantly greater amount of N than any other part of the crop ($P = 0.001$) but there was no significant increase in the N content of any of the plant parts over 96 hours. The timing of application of foliar urea did not significantly affect the amount of N that was taken up by the different plant parts.

Figure 6.4 (d) shows the distribution of N present in a GAI 5 crop at ear emergence and the changes that occurred after the application of 30 kg N ha^{-1} as foliar urea. The greatest proportion of N was present in the top half of the stem where the unemerged ear was located ($P = 0.001$), and this was the only significant increase in N content over the 96 hour period.

The timing of the application of foliar urea with 0.1 % Silwet L-77 did not significantly alter the N content of the leaves and the stem parts (figures 6.4 (e) and (f)). The only differences occurred due to the presence or absence of the ear; only the ear at anthesis showed a significant increase in N content. The application of foliar urea with either Spray-Fix or LI-700 at ear emergence did not significantly alter the N content of any of the leaves. The only significant changes were recorded in the bottom half of the stem which showed a significant increase in the amount of N present after 96 hours. After the application of 60 kg N ha^{-1} to a GAI 5 crop at anthesis (figure 6.4 (i)), only the ear and the flag leaf showed a significant increase in N content over 96 hours.

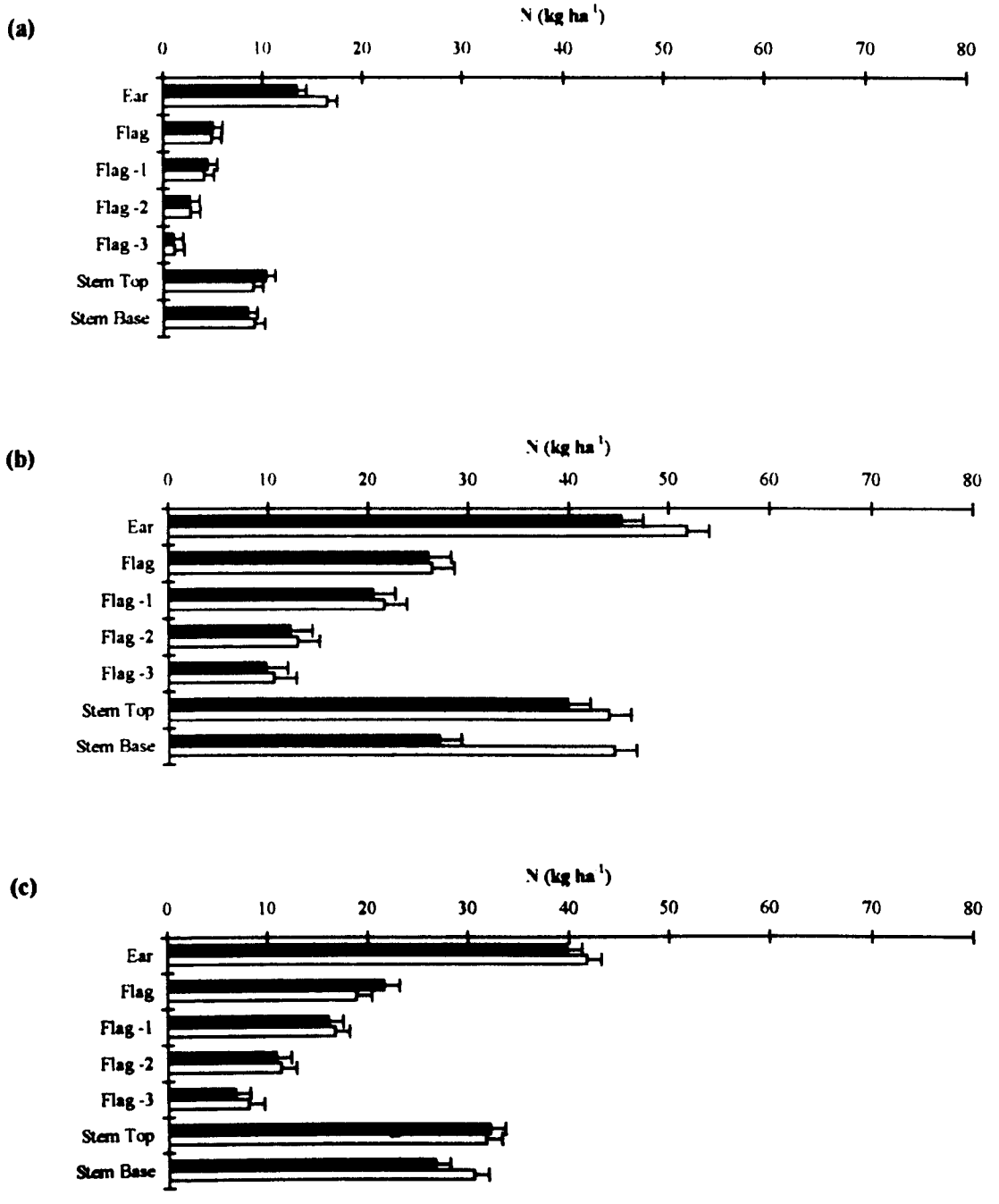


Figure 6.4 The N content (kg ha^{-1}) of individual plant parts of (a) N0, (b) Ncf and (c) GAI 5 crops receiving applications of 30 kg N ha^{-1} as foliar urea made during anthesis at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount present 96 hours afterwards. The SEDs shown have 26 df and are for comparisons between both time and plant part.

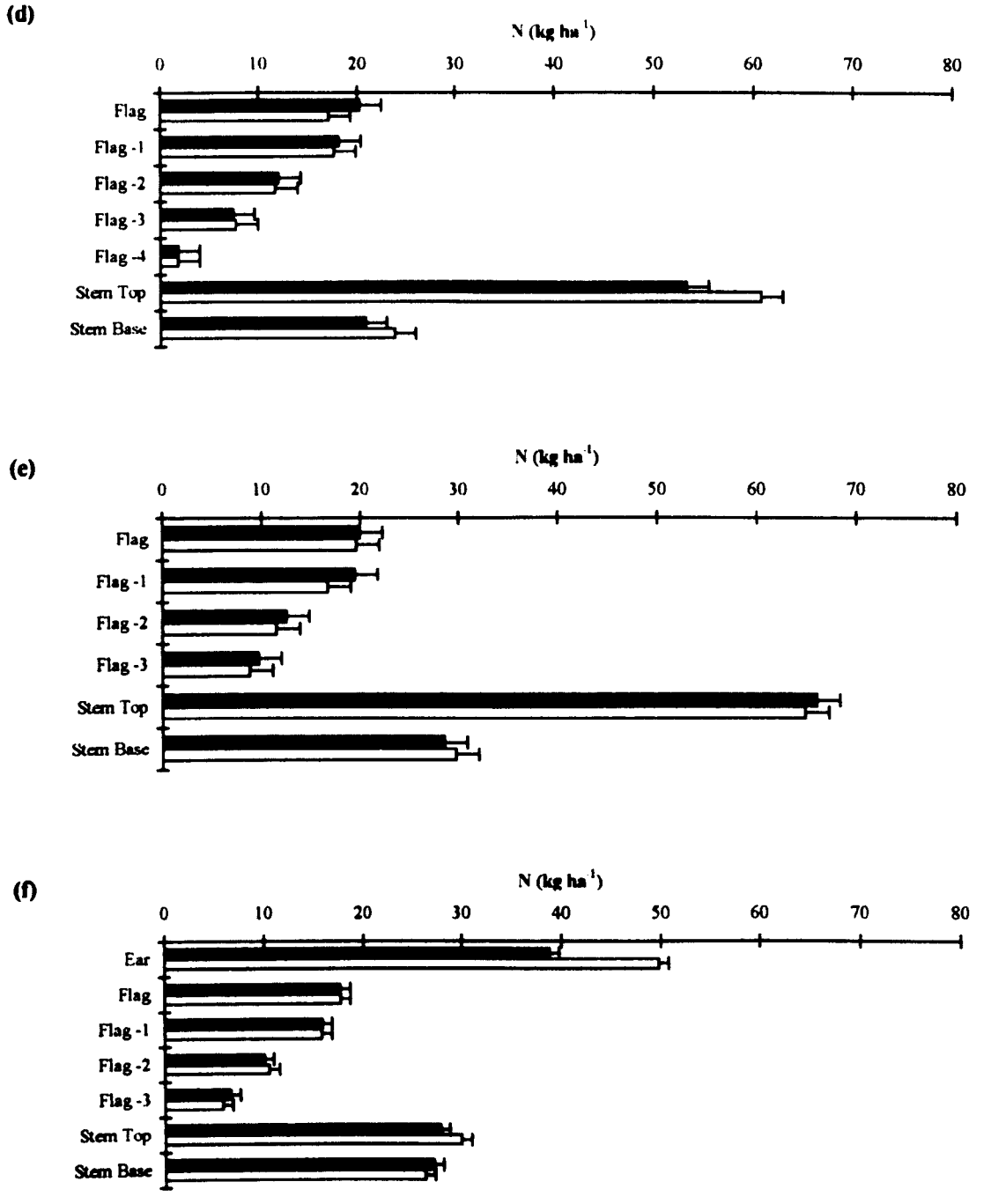


Figure 6.4 The N content (kg ha^{-1}) of individual plant parts of GAI 5 crops receiving (d) 30 kg N ha^{-1} at ear emergence, (e) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at ear emergence, (f) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at anthesis as foliar urea at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount present 96 hours afterwards. The SEDs shown have 22 df (26 df for applications made at anthesis) and are for comparisons between both time and leaf layer.

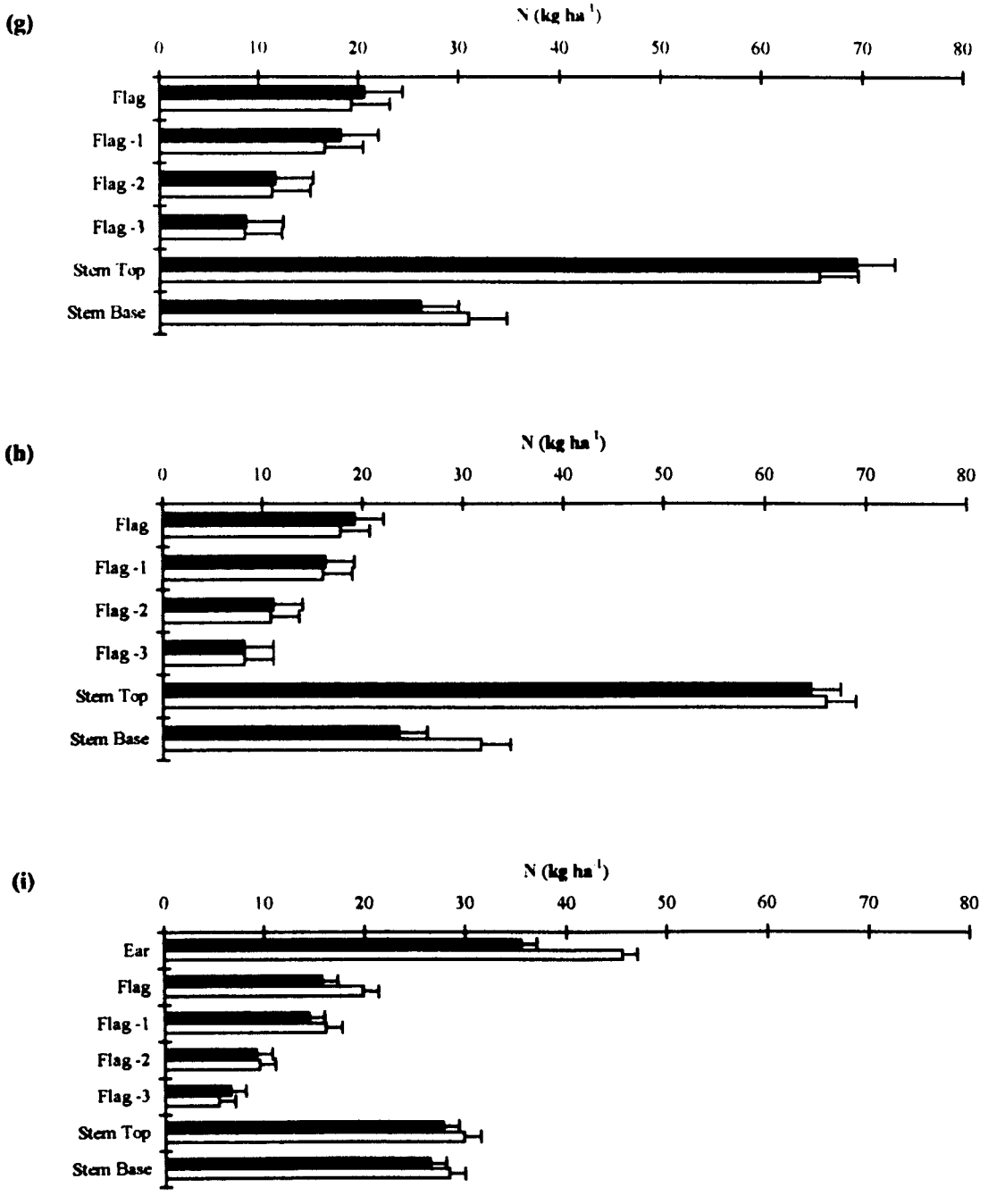


Figure 6.4 The N content (kg ha^{-1}) of individual plant parts of GAI 5 crops receiving (g) 30 kg N ha^{-1} with 0.1 % Spray-Fix at ear emergence, (h) 30 kg N ha^{-1} with 0.1 % LI-700 at ear emergence, (i) 60 kg N ha^{-1} at anthesis as foliar urea at IACR-Rothamsted in 1995. The black bars are the amount present immediately after application and the white bars the amount present 96 hours afterwards. The SEDs shown have 22 df (26 df for applications made at anthesis) and are for comparisons between both time and plant part.

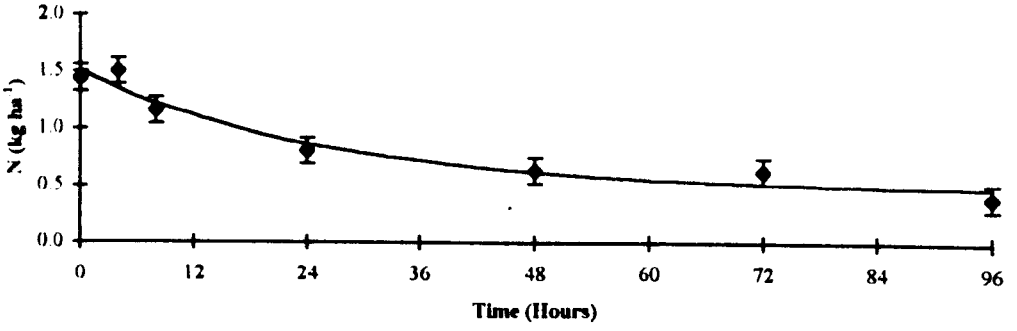
6.4.7 Pattern of loss of N from the surface of the flag leaf and subsequent N uptake

The amount of N present on the surface of the flag leaves was measured at 4, 8, 24, 48, 72 and 96 hours after the initial application of foliar urea: in order to examine the pattern of loss of N from the surface of the flag leaves. Although the total amount of N lost from the flag leaves was significant over the 96 hour period the difference between each of the sample times was not necessarily significant.

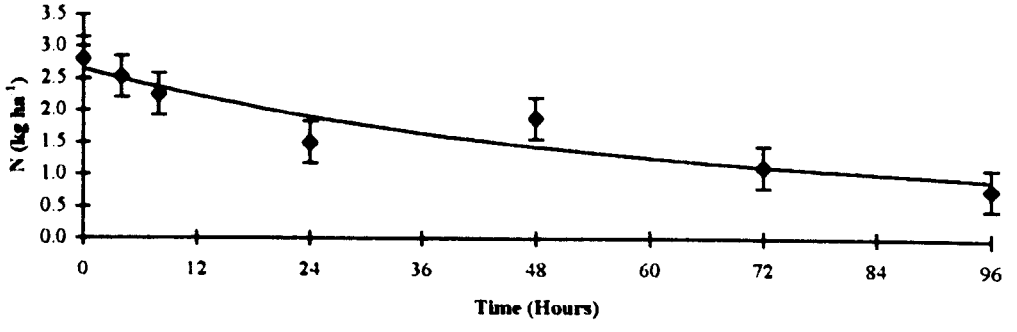
Curves were fitted to the data and are shown in figures 6.5 (a-i). The data for the nine treatments conformed to an exponential curve. The half life ($t_{0.5}$) for the loss of urea from the surface of the flag leaf was calculated as the time taken for half the N initially deposited to be lost and this was used to indicate any differences in the dynamics of loss. Table 6.8 shows the calculated half lives.

The $t_{0.5}$ for the N0 and Ncf crops at anthesis, between which there was no significant difference, was significantly longer than $t_{0.5}$ for the GAI 5 crop, ($P = 0.05$). The timing of the application of foliar urea or the presence of an adjuvant did not significantly affect $t_{0.5}$. Only the application of 60 kg N ha^{-1} as foliar urea resulted in a significant increase in $t_{0.5}$.

(a)



(b)



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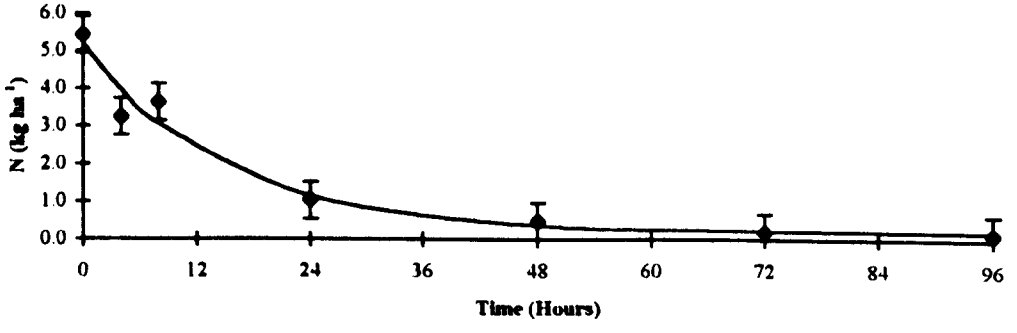
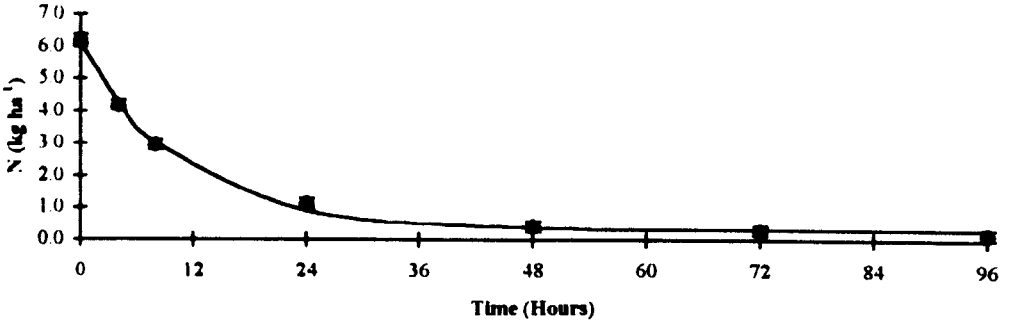
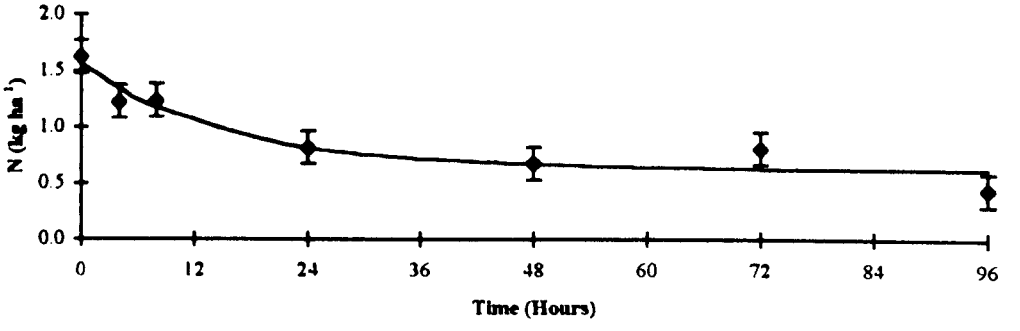


Figure 6.5 The loss of N (kg ha^{-1}) from the surface of the flag leaves of (a) N0, (b) Ncf and (c) GAI 5 crops receiving applications of 30 kg N ha^{-1} as foliar urea during anthesis at IACR-Rothamsted in 1995. The curves are exponential and have r^2 values of 0.930, 0.808 and 0.945 respectively, the SEDs shown have 4 df.

(d)



(e)



(f)

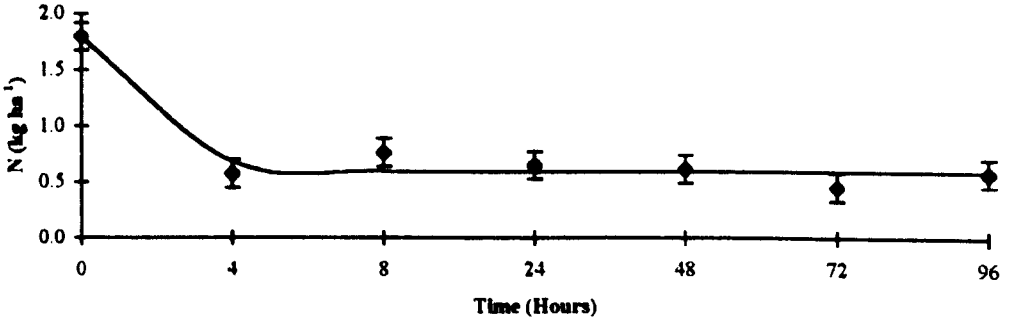
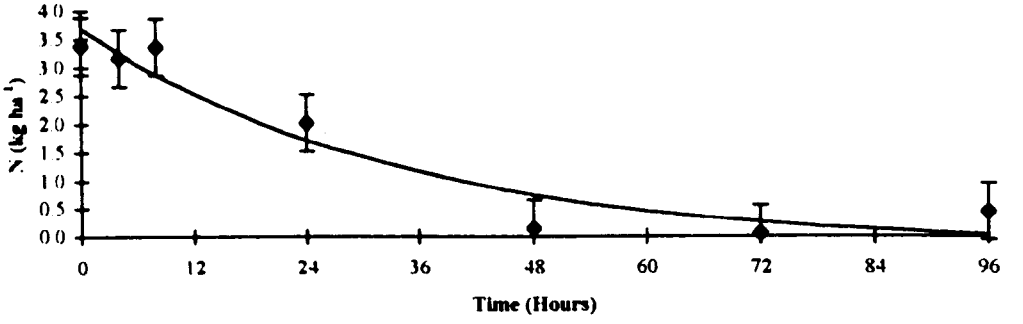
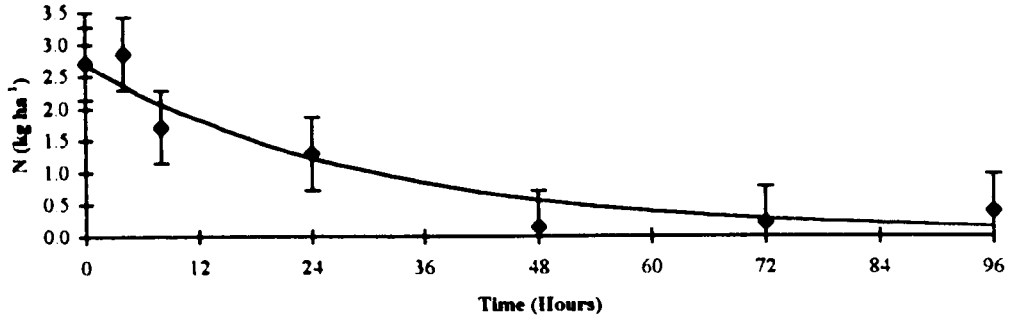


Figure 6.5 The loss of N (kg ha^{-1}) from the surface of the flag leaves of GAI 5 crops receiving (d) 30 kg N ha^{-1} at ear emergence, (e) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at ear emergence, (f) 30 kg N ha^{-1} with 0.1 % Silwet L-77 at anthesis as foliar urea at IACR-Rothamsted in 1995. The curves are exponential and have r^2 values of 0.996, 0.867 and 0.926 respectively, the SEDs shown have 4 df.

(g)



(h)



(i)

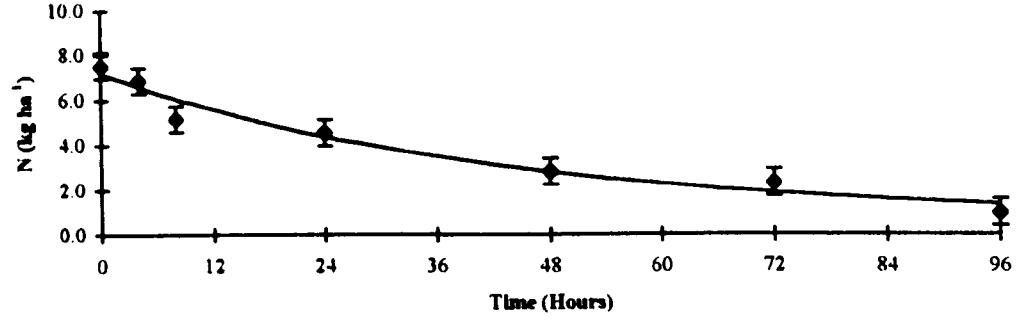


Figure 6.5 The loss of N (kg ha^{-1}) from the surface of the flag leaves of GAI 5 crops receiving (g) 30 kg N ha^{-1} with 0.1 % Spray-Fix at ear emergence, (h) 30 kg N ha^{-1} with 0.1 % LI-700 at ear emergence, (i) 60 kg N ha^{-1} at anthesis as foliar urea at IACR-Rothamsted in 1995. The curves are exponential and have r^2 values of 0.894, 0.752 and 0.941 respectively, the SEDs shown have 4 df.

Table 6.8 Half life (Hours) for loss of urea from the surface of the flag leaves of crops at IACR-Rothamsted in 1995 that received applications of foliar urea.

Treatment	$t_{0.5}$
N0 + 30 kg N ha^{-1} at anthesis	28.0
GAI 5 + 30 kg N ha^{-1} at ear emergence	11.8
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at ear emergence	13.8
GAI 5 + 30 kg N ha^{-1} + Spray-Fix at ear emergence	19.9
GAI 5 + 30 kg N ha^{-1} + LI-700 at ear emergence	16.5
GAI 5 + 30 kg N ha^{-1} at anthesis	9.8
GAI 5 + 60 kg N ha^{-1} at anthesis	32.4
GAI 5 + 30 kg N ha^{-1} + Silwet L-77 at anthesis	2.5
Ncf + 30 kg N ha^{-1} at anthesis	43.2
SED (13 df)	8.66

Corresponding with the loss from the surface of the flag leaf the change in the N content of leaf was also measured at the same time, figures 6.6 (a-e) show this change (kg ha^{-1}) for the 96 hour period after foliar urea had been applied. The N0 crop contained a significantly smaller amount of N in the flag leaves than GAI 5 and Ncf crops ($P = 0.001$), the Ncf crop contained the largest amount. The N content of the flag leaves of the N0 crop did not change significantly over the 96 hours (figure 6.6 (a)). The N content of the flag leaves only showed a significant increase after 24 hours ($P = 0.01$) when foliar urea was applied at ear emergence to a GAI 5 crop (figure 6.6 (d)), and there was then a significant decline in N content to 96 hours. This pattern was not repeated by the application of 30 kg N ha^{-1} at anthesis (figure 6.6 (c)) when a significant increase in N content was recorded immediately and 4 hours after application. This treatment then exhibited

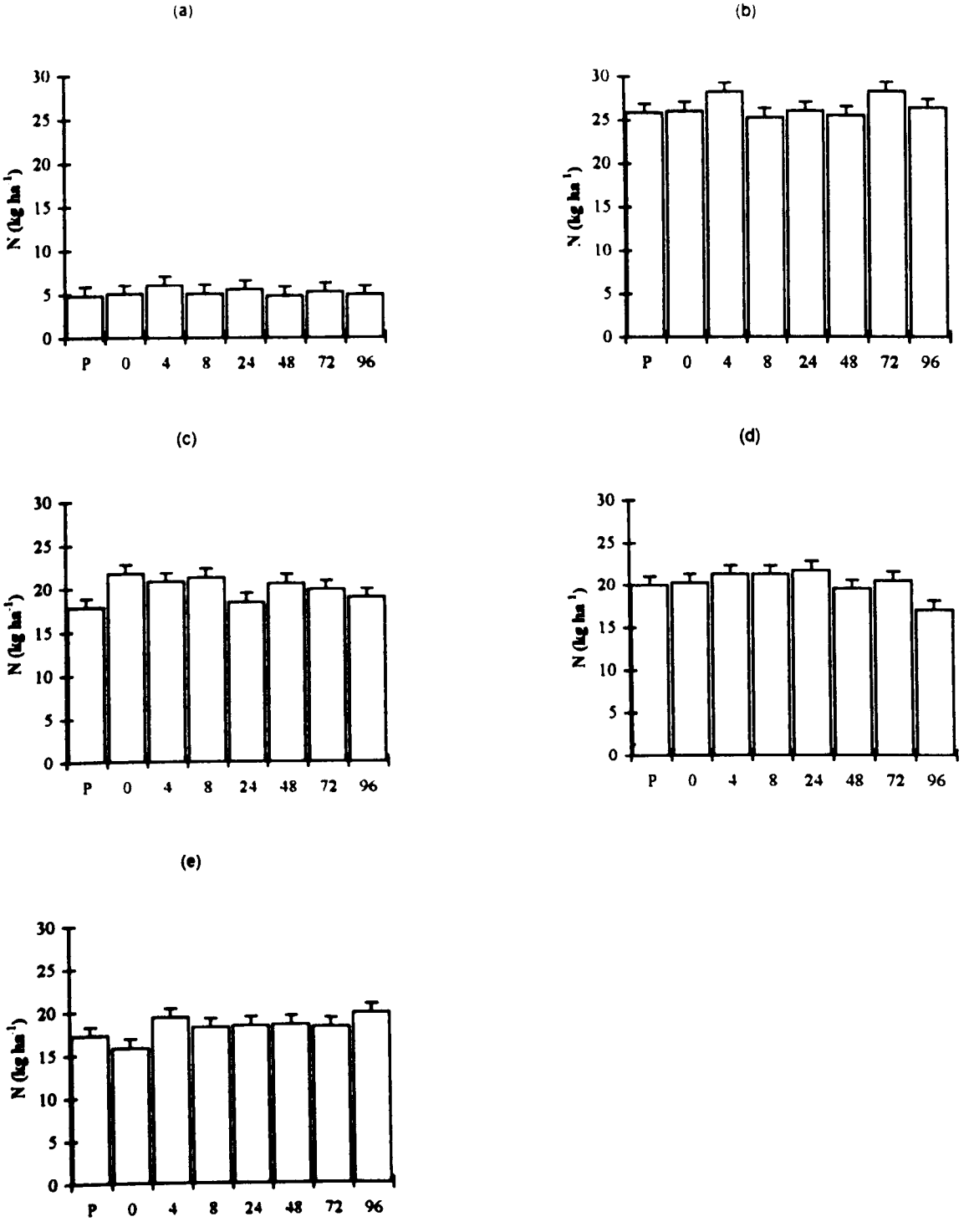


Figure 6.6 The change in the N content (kg ha^{-1}) of flag leaves when measured at intervals over a 96 hour period. The SEDs shown have 14 df, P is the N content before foliar urea was applied. (a) 30 kg N ha^{-1} applied to a N0 crop at anthesis, (b) 30 kg N ha^{-1} applied to a Ncf crop at anthesis, (c) 30 kg N ha^{-1} applied to a GAI 5 crop at anthesis, (d) 30 kg N ha^{-1} applied to a GAI 5 crop at ear emergence, (e) 60 kg N ha^{-1} applied to a GAI 5 crop at anthesis.

non-significant changes in N content for the remainder of the 96 hours. The Ncf crop (figure 6.6 (b)) behaved in a similar way to the GAI 5 crops receiving foliar urea at anthesis, a significant increase in N content was recorded four hours after application and followed by non-significant changes to 96 hours.

6.5 N DEPOSITION AND UPTAKE FROM FOLIAR APPLICATIONS SUTTON BONINGTON 1995

Late-N as foliar urea was applied at anthesis to N0, GAI 5 and Ncf crops. A total of 60 kg N ha^{-1} was applied as two applications of 30 kg N ha^{-1} in 400 l ha^{-1} water. The applications were made one week apart, during anthesis, on 20 and 27 June 1995 to reduce the risk of leaf scorch. For the purposes of assessing the amount of N deposited, only the applications made on 20 June 1995 were measured.

Applications of foliar urea were made at anthesis and were applied under weather conditions that did not alter greatly between the time of application or the end of the period of measurement. Temperatures were quite warm, reaching a maximum of 19.1 °C, the lowest minimum temperature was 9.5 °C. There were approximately 4 hours of sunshine per day and the wind speed was also quite variable but did not exceed the recommended maximum for spraying. There was only 12 mm of rain in the entire month of June and none fell during the duration of the experiments.

6.5.1 **N deposition onto and uptake by the whole crop**

The total amounts of N deposited onto the crops and the amount of N remaining 96 hours afterwards are shown in table 6.9.

Table 6.9 The amounts of N deposited onto the crop canopies immediately after the application of 30 kg N ha^{-1}, the amount remaining 96 hours afterwards and the amount lost from the surface of the crop over that period (kg ha^{-1}) at Sutton Bonington in 1995.

Treatment	**N Deposited**	**% Deposited**	**N Remaining 96 hours**	**% Remaining**	**N Lost 0 - 96 Hours**
N0	6.02	20.1	4.70	15.7	1.32
GAI 5	8.85	29.5	2.80	9.3	6.05
Ncf	8.67	28.9	1.97	6.6	6.70
SED (4 df)	2.262	7.54	1.554	5.18	3.22

SED = 1.800 (10 df) for comparisons between the amount of N deposited and the amount remaining at 96 hours.

The N status of the crop or the size of the canopy did not have a significant effect upon the amount of N deposited, the amount remaining 96 hours after application or the amounts of N lost from the surface of the crop over this time. However, there was significantly less N present on the surface of the GAI 5 and Ncf crops after 96 hours than was present initially ($P = 0.01$); the N0 crop did not lose a significant amount of N over this period.

The amount of N taken up over the 96 hours of the experiment was measured on samples of the crop that had been washed to remove any N present on the surface. The data obtained are shown in table 6.10.

The N0 crop contained a significantly smaller amount of N than the GAI 5 and Ncf crops, the Ncf crop contained a significantly greater amount of N than the GAI 5 crop ($P = 0.001$) and this remained the case 96 hours after the application of foliar urea. Although all these crops showed an increase in N content after the application of foliar urea, the differences were not significant.

Table 6.10 The initial N content, the amount present 96 hours afterwards and the N taken up by the crop (kg ha^{-1}) after the application of 30 kg N ha^{-1} as foliar urea on 20 June at Sutton Bonington, 1995.

Treatment	N Content of Washed Crop		N Uptake
	Initial	96 Hours	
N0	61.5	66.7	5.2
GAI 5	95.5	108.8	13.3
Ncf	139.5	145.4	5.9
SED (4 df)	7.45	7.97	22.98

SED = 13.63, 10 df for comparisons between the initial N content and the amount present at 96 hours.

6.5.2 N deposition onto stratified layers and penetration into the canopy

There were no significant differences in the amounts of N deposited onto each leaf layer of the crops or the amount of N remaining 96 hours after application (figures 6.7 (a - c)). The ear, flag leaf and flag - 1 were the most important organs for the deposition of N, collectively responsible for more than 60 % of the total deposited and it was only from these three organs that there was a significant loss of N over the 96 hour period ($P = 0.05$).

6.5.3 N uptake by the individual plant parts

Figure 6.8 (a - c) shows how the N present in the whole crop was distributed between the individual plant parts. The ear contained significantly more N than any other organ for all three crops and was the only organ to show a significant increase in N content after the application of foliar urea when measured over a 96 hour period ($P = 0.001$) with the biggest increase being shown by the ear of the GAI 5 crop. There were no significant changes in the N content of the leaves or the two halves of the stem. The application of

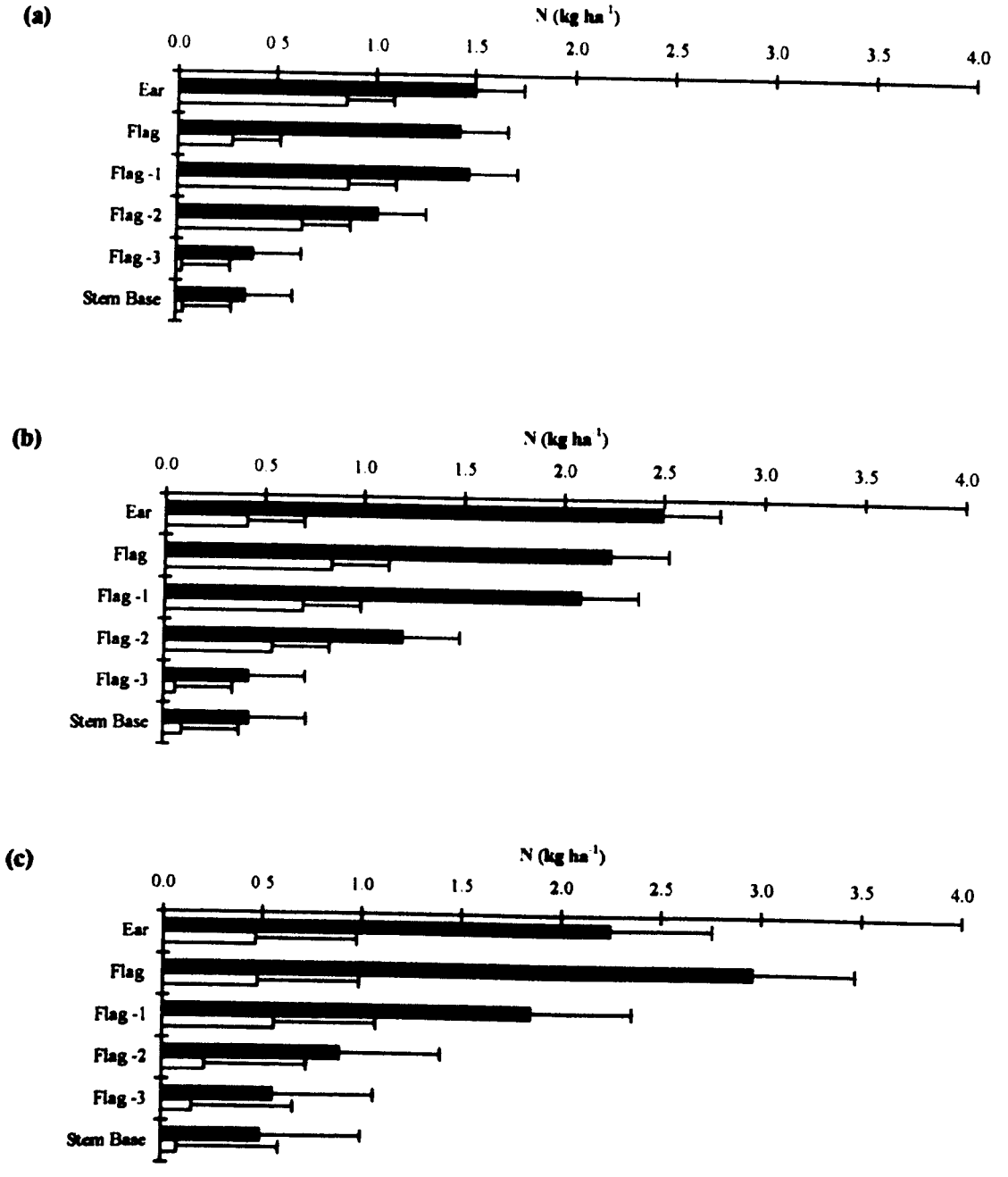


Figure 6.7 The deposition of N (kg ha^{-1}) onto stratified leaf layers of (a) N0, (b) Ncf and (c) GAI 5 crops from applications of 30 kg N ha^{-1} as foliar urea during anthesis at Sutton Bonington in 1995. The black bars are the amount present immediately after application and the open bars the amount remaining 96 hours afterwards. The SEDs shown have 20 df and are for comparisons between both time and leaf layer.

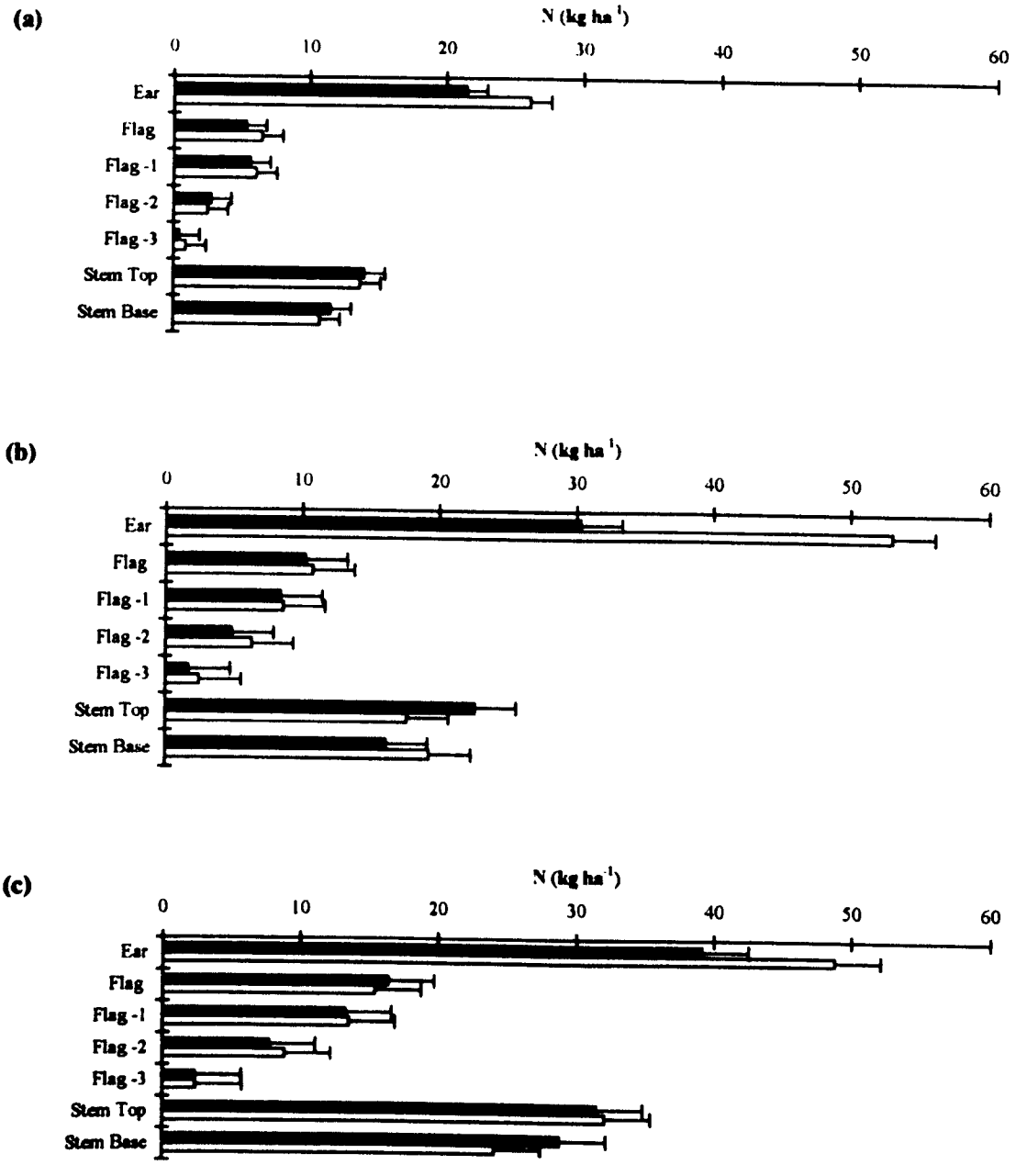


Figure 6.8 The N content (kg ha^{-1}) of individual plant parts of (a) N0, (b) Ncf and (c) GAI 5 crops receiving applications of 30 kg N ha^{-1} as foliar urea during anthesis at Sutton Bonington in 1995. The black bars are the amount present immediately after application and the white bars the amount present 96 hours afterwards. The SEDs shown have 22 df and are for comparisons between both time and plant part.

foliar urea did not affect the concentration of N found in any of the plant organs.

6.6 DISCUSSION AND CONCLUSIONS

The results reported in this chapter clearly show that foliarly applied N was intercepted by crops of varying canopy size and N status, that the N present on the crop surface was 'lost' by a combination of uptake and volatilization, which, judging by the amount present in the crop at harvest was probably predominantly uptake.

The experiments described in section 6.2 of this chapter indicate that the method used to determine the amount of N present on the surface of the plant material provided reasonably accurate and repeatable results, with up to 92 % of the amount applied recovered during the washing process. There was little loss of urea during storage at -20 °C or during defrosting for analysis.

The difference in the amount of N applied by the track sprayer and that measured as present on either artificial acetate targets or on individual leaves, was quite large, section 6.2.2. Approximately 78 and 44 % of the amount of N applied, was deposited onto the acetate strips and leaves respectively. It is possible that differences in the nature of the surface of either the acetate or the leaf, contributed to changes in the amount of spray solution lost by bounce off. This subject is discussed more fully in section 7.7. However, it is perhaps unrealistic to expect a large proportion of the spray applied to be intercepted by a strip of acetate or a leaf which were only a few centimetres wide. Spray droplets were also deposited on the perspex used to keep the leaves and acetates horizontal and there would have been penetration to ground level. Spray drift may also have been exacerbated by the movement of the strip sprayer.

6.6.1 **Foliar urea applied at IACR-Rothamsted in 1994**

The measurements of N deposition from foliar urea applications in the 1994 experiment at

IACR-Rothamsted were subject to large errors caused by the handling of the plant material too soon after application and before the applied urea had dried. Therefore, although some N was detected on the leaf surface, it was not possible to determine exactly how much had initially been present. As a result, the only conclusions that can be drawn from these measurements were that N was deposited onto the crop by foliar urea sprays and an increase in the N content of the crop was recorded after 48 hours. The total amounts measured as present on the leaves, were much smaller than might have been expected, as less than half the N applied was measured as being intercepted by the crop. This was almost entirely due to the errors in the experimental technique described above. Loss by deposition onto the soil surface probably only accounted for a small proportion of the amount that was missing; estimates for this vary between 5 and 10 % (T. Robinson, personal communication) and it is unlikely that there were significant volatilization or evaporation losses.

It was clear that the flag leaf was the most important organ for interception of N, with flag - 1 and the ear also intercepting a significant proportion of the total. There was little measured penetration to the bottom layers of the canopy probably because the upper layers of the flag leaf and flag-1 and, when present, the ear, together presented a dense surface that did not have many gaps to allow penetration below this layer. It is also possible that the real distribution of N deposition was obscured by the experimental errors discussed above and that there was greater penetration than was actually recorded.

As a result of the problems outlined above and the errors in the data that resulted, the technique for sampling the plant material was altered as outlined in section 6.1.2, to ensure that the data obtained in 1995 was more reliable.

In the following sections the data obtained from measurements made at IACR-Rothamsted in 1995 and Sutton Bonington in 1995 are discussed together as the data were recorded using the same techniques and jointly lead to similar conclusions.

6.6.2 N deposition and penetration into the canopy

The applications of foliar urea in the field experiment at IACR-Rothamsted in 1995 provided a much more detailed insight into the dynamics of N deposition onto the crop and subsequent uptake. The total amount of N deposited onto the crops was quite variable, ranging from a maximum of 65 % of the amount applied to 26 %. These values compare favourably with those reported by Readman (1996), who found that a maximum of 35 % urea (16 % N) was intercepted when 30 kg N ha^{-1} as foliar urea was applied at the beginning of stem extension. Readman's treatments were applied much earlier in the development of the plant than in the present study, the foliage would have been more low growing and prostrate than during later applications and it would be reasonable to expect considerable deposition onto the soil surface, a maximum of 70 % was recorded in that study. It has been suggested that at the beginning of stem extension 50 % of a spray would be deposited onto the crop and 50 % onto the soil surface (T. Robinson, personal communication). This value for deposition onto the crop was similar to the amount intercepted from some of the applications of foliar urea with adjuvants, applied at IACR-Rothamsted in 1995, albeit at much later growth stages. The adjuvants may have altered the dynamics of deposition, by changing the characteristics of the spray as it was deposited onto the leaves, either spreading out the droplets or sticking them to the surface, however there may have been a greater potential for evaporation or greater penetration to the lower layers of the canopy and the soil surface.

The total amount of N intercepted by the N0 crop was very small, 26 % of the total N applied. Although, it would be reasonable to expect that smaller crop canopies and therefore smaller leaves would intercept less N, as was the case in this treatment, it was the large distance between each of the individual plants and the near vertical orientation of the leaves that were probably the most important factors. Despite this, N was evenly distributed over the ear and all the leaves, despite the decreasing potential for deposition with increasing depth into the canopy, (Bache, 1985). Had the leaves had a more horizontal orientation it would be reasonable to expect that more N would have been

deposited in total. However, calculated as a percentage of the amount of N intercepted there was increased penetration to the lower leaf levels in the N0 crop compared with the GAI 5 crops.

Although there were no significant differences in the GAI and number of shoots m^{-2} of the Ncf or the GAI 5 crops, a significantly smaller amount of N was deposited onto the Ncf crop. It is possible that the orientation of the flag leaves of the Ncf crop were sufficiently different to those of the GAI 5 crop, that an upper surface layer was formed which produced different characteristics of air movement and turbulence as the spray boom passed, resulting in greater losses of the smallest spray droplets by evaporation and drift, reducing deposition on and penetration into the canopy. As measurements of canopy architecture were not made, there are no data to support this theory, however there were no significant differences in the area of the flag leaves of the two crops.

The flag leaf was the most important organ for interception of N and the top half of the canopy accounted for over 50 % of the total amount of N intercepted. This pattern is typical of deposition from spray applications; Bache (1985) described similar deposition patterns. It is clear that the growth stage at which foliar urea was applied did not alter the total amount that was deposited onto the GAI 5 crop. When present the ear intercepted approximately 12.5 % of the total and this was compensated for by increased interception by the flag -2 and flag -3 leaves when applications were made when the ear had not emerged. This was also true when foliar urea was applied with the spreader Silwet L-77, although a smaller total amount was deposited onto the crop. This reduction in the total urea deposited may have simply been the result of the spreader increasing the spread of the solution on leaf surfaces and increasing the surface area from which uptake could occur and causing rapid uptake before the initial measurements could be made. This may also help to explain the effects that the other adjuvants had on total deposition. Spray-Fix, a sticker, is supposed to increase the rainfastness of the active ingredient and so as the total deposited was not statistically different from that deposited when an adjuvant was not used, this adjuvant did not have an additional positive effect under these conditions, no rain fell during

measurement of this treatment. The penetrant, LI-700 may also have had a beneficial effect on uptake in the minutes following application, but this adjuvant is usually used for the uptake of charged compounds and urea is uncharged. However, the data presented in this chapter do not test these suppositions.

The application of 60 kg N ha^{-1} showed that N was not deposited more efficiently than when 30 kg N ha^{-1} was applied. A greater proportion of N was intercepted from the smaller application than from the larger one (65 % compared with 50 %). Readman (1996) found that the application of increasing amounts of N as foliar urea (60-120 kg N ha^{-1}) resulted in the percentage of urea intercepted by the crop declining from one third to 13 %, a response similar to that at IACR-Rothamsted in 1995.

There were no significant differences in the total N content at final harvest of the GAI 5 crops that had received applications of foliar urea, indicating that ultimately, the timing and method of application did not have an impact on the potential benefits to be gained by these applications.

Similar results were obtained at Sutton Bonington in the same year. The N0 and Ncf crops both intercepted less N than the GAI 5 crop from applications of 30 kg N ha^{-1} at anthesis, but the differences were not significant. However the total amounts deposited onto the Ncf and GAI 5 crops were much smaller than the amounts recorded at IACR-Rothamsted. The main difference was in the method of application, as at Sutton Bonington a tractor mounted sprayer was used as compared to a knapsack sprayer at IACR-Rothamsted. The tractor may have caused more wind movement and therefore plant movement within the crop due to increased air turbulance and this may have contributed to the reduction in the amount of N measured as present on the surface of the crop. Different nozzles were also used, Lurmark 03-F110 at IACR-Rothamsted and Lurmark 05-F110 at Sutton Bonington. The 05-F110 produced a coarser spray composed of a greater proportion of droplets with a large volume median diameter (*i.e.* the spray was predominately composed of larger droplets), but this would have reduced losses by spray drift and evaporation before

impaction, which are more important in finer quality sprays.

Both the N0 and Ncf crops had a more even distribution of N on the leaf layers than the GAI 5 crop, despite there being no statistical differences in the amount present on the leaf surfaces. It seems that the GAI 5 crop probably had leaves that were more horizontally orientated than the N0 and Ncf crops, intercepting more N in total and illustrating that with increasing depth into the canopy there was less N available for deposition, something that was shown by all the crops (figure 6.7).

The stratified sampling of all the crops to which foliar urea was applied showed that, almost without exception, the flag leaf was the most important organ for interception of N. When foliar urea was applied to the GAI 5 crops, up to 30 % was deposited onto the flag leaf. As has been discussed previously, the upper layers of the canopy, are the most important area for the deposition of N, within this horizontally orientated leaves intercept a greater amount of N.

N that was not intercepted by the crops was subject to several sources of loss. Firstly, it was simply not possible to account for all of the liquid leaving the sprayer. The droplets produced by the nozzles are of varying sizes, from less than 100 μm to greater than 400 μm in diameter, and the quality of the spray is determined by the size range within which the greatest proportion of droplets fall. For these applications, a medium quality spray was used in which the greatest numbers of droplets were 201 - 400 μm in diameter. However, droplets of other sizes were still present, the very smallest of which have the greatest chance of evaporation or loss through drift and turbulent air movement before impaction on the intended target (Matthews, 1982). It is unlikely that there were significant volatilization losses before the N present directly after spraying could be measured, as only a few minutes elapsed before measurements were taken. Spray that penetrated to the lower layers of the crop canopy that was not intercepted by the plant would have been deposited onto the soil surface, but unfortunately the amounts reaching the soil were not measured. However the more open N0 canopy, which had large spaces between the individual plants, would

probably have lost a greater proportion of the N to the soil surface than the denser GAI 5 and Ncf crops. This N may not have been permanently unavailable to the crops, if it was not lost by volatilization. This is higher in the soil than on the leaf surface due to the larger numbers of ureolytic bacteria; however rain could have washed the N into the soil allowing the potential for uptake for roots near the soil surface.

6.6.3 N loss and uptake

The term "loss" has been used throughout this study to define the disappearance of N from the surface of leaves or stems. Bowman and Paul (1990 b) measured the loss of N from the surface of leaves of tall fescue and found that only 5.3 % of the applied N was lost by volatilization in the first 48 hours after foliar urea application. They attributed the majority of the amount of N lost from the leaf surface to uptake. Bowman *et al.*, (1987) found that there was little urease activity on the surface of *Poa pratensis* leaves after foliar urea application. They suggested that this reduction in urease activity was due to the drying of the urea onto the leaf surface, something that occurred within the first four to six hours in these experiments.

The patterns of loss of N from the leaf surface for the experiments carried out at IACR-Rothamsted in 1995 were all exponential through time, indicating that the absolute rate of loss of N was constantly changing. The data presented by Bowman and Paul (1992; 1990 a; 1990 b and 1989), Klein and Weinbaum (1985) and Klein and Zilkah (1986) all present patterns for the loss of urea from the leaf surface that were either similar to or conformed to an exponential pattern of loss irrespective of the amount of N present initially and collectively they suggest that the major part of this lost N could be accounted for by uptake. Klein and Weinbaum (1985) showed that 95 % of the urea applied to olive and almond leaves was taken up within 96 hours and over a similar time period 90 % was taken up by apple leaves (Klein and Zilkach, 1986). Bowman and Paul (1990 b) measured 55 % uptake using N^{15} labelled urea on tall fescue and creeping bent grass turf in a 96 hour period. These reports suggest that the loss from the leaf surface seen in the present

experiment was predominantly uptake of N into the leaf rather than loss by volatilization. The changes in total N content of the whole plant soon after application did not support this (Table 6.7), but this was reflected in the total N content of the plant measured at final harvest (Chapter 4). Figure 6.6 shows the change in N content of the flag leaves measured over 96 hours and indicates that the N content fluctuated over 96 hours. When each stratified layer was examined separately (Figure 6.4) the greatest changes in N content were recorded in the ears, at anthesis or in the top half of the stem, prior to ear emergence. This was also true for the N0, GAI 5 and Ncf crops at Sutton Bonington. Over the 96 hour period it is probable that N was taken up by the leaves and then transported directly to the ear.

Half life measured at IACR-Rothamsted in 1995 indicated that N appeared to be lost more rapidly at anthesis from the flag leaves of GAI 5 crops, than at other stages of development, $t_{0.5}$ was also affected seemingly by the N status of the crop. The GAI 5 crops were probably in the best physiological condition to take up the applied N most rapidly. N0 crops, which were deprived of N and therefore lacking the normal healthy function of an adequately fertilized crop, may not have been able to take up and assimilate the N as rapidly as one with sufficient N available to it. Hence the increase in the time for $t_{0.5}$ for the N0 crop. If this argument is extended the Ncf crop, which in theory, had sufficient N for growth and yield, it might be expected to have a very rapid rate of uptake and therefore a much shorter $t_{0.5}$, than for the GAI 5 crops. However this was not the case and the slow rate of uptake and long $t_{0.5}$ of the Ncf crop might be explained by a feed-back mechanism within the leaf, reducing N uptake when sufficient N was already available so that the amount required for normal function was not exceeded. Alternatively, a leaf well supplied with N may have had a thicker cuticle increasing the time for penetration and uptake.

The adjuvants produced varying results. Spreading the N over the surface of the leaf and so increasing the area over which uptake could occur, might be expected to decrease $t_{0.5}$. This was the case when foliar urea was applied with Silwet L-77 at anthesis but not at ear emergence. Further studies are required to confirm these effects. Stevens, Gaskin and

Hong (1991) found that Silwet L-77 did not increase the rate of cuticular penetration of deoxyglucose in wheat or the total uptake, but uptake was found to follow an exponential pattern with time in both wheat and oats. Silwet L-77 may, in some circumstances, have an antagonistic effect on foliar uptake. Gaskin and Stevens (1993) found that initial rates of glyphosate uptake by wheat and wild grasses were increased but subsequent rates were slower and in wheat total uptake was reduced. It was suggested that this antagonism was related to the high concentration of the adjuvant in solution and has also been found to be a common occurrence with some other adjuvants (Nalewaja, Matysiak and Freeman 1992).

A number of assumptions were made in the calculation of half lives ($t_{0.5}$), N lost from the leaf surface was assumed to be in an exponential decay pattern. During an exponential decline, the proportion of N lost remains constant but the amount lost and therefore the amount remaining changes with each time increment, suggesting that uptake is responsive to the amount of N present on the leaf. Holloway, P.J. (personal communication) suggested that diffusion was the main mechanism for uptake and that a concentration gradient was formed across the cuticle. This corresponds with the data presented showing that loss was exponential, a high concentration on the surface of the leaf initially would result in rapid uptake and as the concentration on the leaf surface declined relative to that within the leaf, so would the rate of uptake. Certainly, where the amount of N present on the leaf surface initially was high, $t_{0.5}$ appeared to be more rapid, compared to when initial amounts were small.

If there was a feed back mechanism regulating the rate of uptake where sufficient N was already available (*i.e.* in the Ncf crop), it would indicate that uptake was active. However, as the initial N content of the Ncf crop was higher than that of the GAI 5 crops, uptake by diffusion could be expected to be slower than when there was a lower N content in the plant, as the difference in concentration between the N on the leaf surface and inside the leaf would not be as great. Therefore this suggests that uptake by the leaf was not an active process and it is unlikely that it was regulated by a feed-back mechanism. $t_{0.5}$ for 60 kg N ha^{-1} was longer than that for 30 kg N ha^{-1} and this suggests that although the

amount of N present on the leaf initially was greater, uptake was not as rapid because a maximum rate of assimilation had already been reached.

The data obtained from the experiment at Sutton Bonington showed a discrepancy between the amount of N measured as deposited onto the crop canopies and the amount taken up, measured as the change in N content of the whole plant. A larger amount of N was apparently taken up than was deposited onto the N0 and GAI 5 crops. However, there was a large amount of variability within the data for the N content of the whole plant, suggesting that these data may not give a true picture of the amount of N taken up. The individual replicates show that there was one replicate in each treatment (a different block on each occasion) in which the increase in N content was significantly larger than in the other replicates and this was responsible for the large mean increases in each case. Removing the increases that were greater than the total amount of N applied as foliar urea, resulted in a non-significant change in the N content of the whole crop over 96 hours, similar to the responses recorded at IACR-Rothamsted in the same year. Probably the amount of N deposited onto the crop surface initially was underestimated.

It can be concluded that N was deposited onto the surface of the crop canopy and then subsequently lost from the surface of the leaf. This loss was probably a combination of a small volatilization loss and a larger uptake.

Chapter 7: STUDIES IN CONTROLLED CONDITIONS

7.1 N^{15} EXPERIMENT

7.1.1 Introduction

The aims of this experiment were to obtain a total N balance for the application of foliar urea, such that if the amount that had been applied to the leaf and the amount that was present in the plant material was known, the difference between these two values would be the amount lost through volatilization. The second purpose was to examine the fate of foliar urea after uptake by the leaf, determining whether the applied N was transported directly to the ear or whether it remained either in the flag leaf or in other leaves and the stem. A known weight of N^{15}-labelled urea was applied to the flag leaves of plants at anthesis grown under controlled environment conditions and the dynamics of urea loss from the leaf surface and movement of N^{15} about the plant were studied over a 96 hour period.

7.1.2 Materials and methods

7.1.2.1 *Experimental design*

The N^{15}-labelled urea was applied using a small hand operated plant mister set to deliver a relatively fine spray, every squeeze of the spraying mechanism delivered 0.75 ml of solution. A 5 per cent urea solution was applied that contained a five per cent enrichment of N^{15}.

For spraying, the flag leaves of three plants were held on perspex sheets by attaching the tip with a known weight of sticky tape and a sheet of filter paper (Whatman No. 1) was placed between the leaves and the perspex. A second, weighed sheet of filter paper was arranged in front of the stems and ears to intercept any spray drifting to these parts. Three deliveries

of 0.75 ml of spray were applied to the flag leaves. The mister was weighed before and after the spray application. The leaves were then allowed to dry for approximately one minute before being released, care was taken to avoid sudden movement or touching the sprayed leaves that might have dislodged or relocated the spray deposit. Both the sheet protecting the remainder of the plant and the perspex sheet were reweighed.

The experiment consisted of three replicates of plants to be sampled on nine occasions during the 96 hours after spraying. Each replicate contained three plants to provide sufficient plant material for analysis of the surface urea washings and the N^{15} within the plant.

For N^{15} analysis plants were divided into the flag leaf, ear and a bulk of the remaining leaf and stem material. Samples were taken prior to application of N^{15} to determine the background levels of N^{15} in the plant. The roots and the perlite/terra green growth medium were sampled at the beginning and end of the experiment to quantify the extent of N^{15} excretion from the roots to the growth medium (P.R. Poulton, personal communication).

The three flag leaves within each replicate sample were cut off immediately above the ligule and placed directly into 200 ml of 0.1 % Triton X-100 solution for ten minutes to remove any urea present on the surface. The plants were sampled prior to urea application, immediately afterwards and then at 4, 8, 12, 24, 48, 72 and 96 hours after application. The solutions were frozen separately and the area of flag leaves, ears, other leaves and stems were measured individually and their dry weights determined after drying at 80 °C for at least 24 hours. The amount of urea present in the washing solutions was determined by the diacetyl monoxime assay.

7.1.2.2 *Analysis of N^{15}*

The plant samples were milled to a very fine powder in a Teamer mill and the total N and the N^{15} content of the plant samples was determined by atomic absorption mass

spectrometry using a RoboPrep Linked Automatic Nitrogen and Carbon Analyzer, (Europa Scientific Analytical Services, Crewe, England). For this, a known weight of plant material (5 - 15 mg, depending upon the anticipated N content of the sample), was placed in a tin foil capsule and combusted at 1020 °C in oxygen to produce carbon dioxide, water and oxides of N - N_xO_y gas. This mixture of gases was then passed through a copper reduction furnace at 600 °C to remove the oxygen from the oxides of N, producing N_2 gas, water vapour and carbon dioxide. The water vapour and carbon dioxide were removed in two scrubber tubes using magnesium perchlorate and Carbosorb AS (Merck). The pure N_2 gas was then passed into the mass spectrometer, where the molecules of N_2 were ionized and the N passed through a magnetic field to determine the total amount of N^{14} and N^{15} present. Chemical standards of glycyrrhizic acid monoammonium trihydrate salt 98 %, were used for calibration. Samples of plant material of known N content were used as standards and empty tin capsules were burnt to provide a blank value.

7.1.2.3 *Calculations of N^{15} content*

The method used to calculate the recovery of N^{15} - labelled urea was based on the equation used by Hauck and Bremner (1976) and Powlson, Poulton, Moller, Hewitt, Penny and Jenkinson (1989).

$$F = T\left(\frac{p-q}{f}\right)$$

where : F = N in crop derived from labelled fertilizer

T = total N in crop

p = atom per cent excess N^{15} in labelled sample of crop

q = atom per cent excess N^{15} in control sample of crop that did not receive labelled fertilizer

f = atom per cent excess N^{15} in labelled fertilizer that was applied

and T is calculated by:

$$T = M\left(\frac{n}{100}\right)$$

where: M = total dry weight of the plant material

n = percentage N in plant material

The percentage recovery of labelled N in crop is calculated by:

$$\frac{F}{Q} \times 100$$

where: Q = mass of labelled N applied.

T, F and Q are all expressed as mg.

7.2 RESULTS

7.2.1 Uptake and loss of N^{15}

There was significantly less N^{15} present on the surface of the flag leaf ($P = 0.001$, SED = 0.03688, 14 df) and significantly more N^{15} present in the whole plant ($P = 0.01$, SED = 0.0636, 13 df) 96 hours after application than was present initially. The changes in the amount of N^{15} present in solution (washed from the surface of the flag leaf) and in the plant over the 96 hour period, when expressed as a percentage of the amount that was present on the surface of the leaf initially both conformed to an exponential curve, $r^2 = 0.847$, SED = 9.26, 5 df and $r^2 = 0.921$ SED = 7.92, 5 df respectively, (figure 7.1 (a)). The variation in the values for the percentage of N^{15} present in the plant were high, mostly

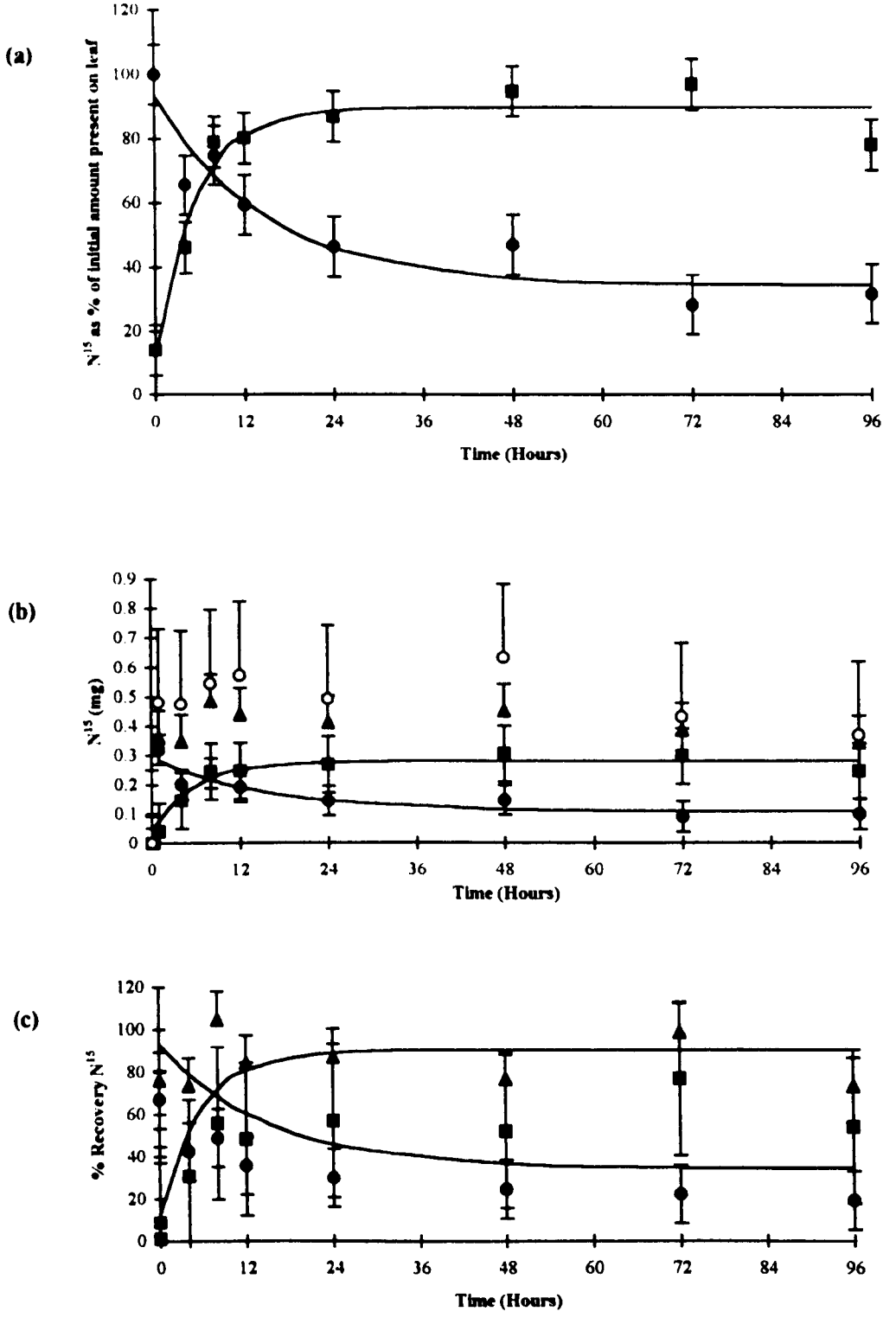


Figure 7.1 (a) The amount of N^{15} recovered from the leaf surface (in the washing solutions) and in the plant expressed as a percentage of the amount present initially on the leaf, (b) the actual amount (mg) of N^{15} recovered and (c) the percentage recovery of N^{15} expressed as a proportion of the amount of N^{15} applied. The SEDs shown have 13 df. ● N^{15} in solution, ■ N^{15} in plant, ▲ total, ○ amount of N^{15} applied.

between 80 and 100 %; this was because the amounts of N^{15} applied to the plants at each time period were not the same, despite the intention that that would be the case. Therefore these data give only an indication of the dynamics of both loss from the surface of the leaf and uptake into the plant.

When the data are expressed simply as the amount of N^{15} present as milligrams both in the plant and on the leaf surface the same pattern was observed, fitting to an exponential curve ($r^2 = 0.395$, SED = 0.0956, 21 df and $r^2 = 0.631$, SED = 0.0512, 21 df). Figure 7.1 (b) shows this and also the total amount of N^{15} accounted for in solution and in the plant (▲), (SED has 13 df) and the amount of N^{15} applied (O). The total present on the leaf and in the whole plant varied with the amount of N^{15} that was applied initially, although there were no significant differences in the amounts applied for each time sample (SED = 0.1216, 13 df). The difference between the total amount of N^{15} accounted for (in the plant and in solution) and the amount applied are thought to be caused by variation in the amount of spray bouncing off the leaf, drifting away or evaporating before impact. In order to avoid this problem a percentage recovery was calculated from the amount of N^{15} applied at each sample time, Figure 7.1 (c). However, the data were very variable and although an increase and decrease in N^{15} content of the plant and washing solution was shown, they did not conform to an exponential curve with sufficient accuracy to allow this relationship to be confirmed for this measure, ($r^2 = 0.304$, SED = 36.2, 21 df and $r^2 = 0.701$, SED = 13.7, 21 df respectively for the percentage recovery of N^{15} in the plant and in solution). The total percentage recovery from the leaf surface and from the plant was approximately 80 % of the amount applied, of which 60 % was present in the plant and 20 % on the leaf surface and the remaining 20 % was probably lost through spray drift, volatilization and experimental inaccuracies.

7.2.2 Fate of N and N^{15} in the plant

Figure 7.2 (a) shows the total N content (mg) of the flag leaf, ear, rest of the plant and the whole plant over 96 hours and although there was a significant increase in the total amount

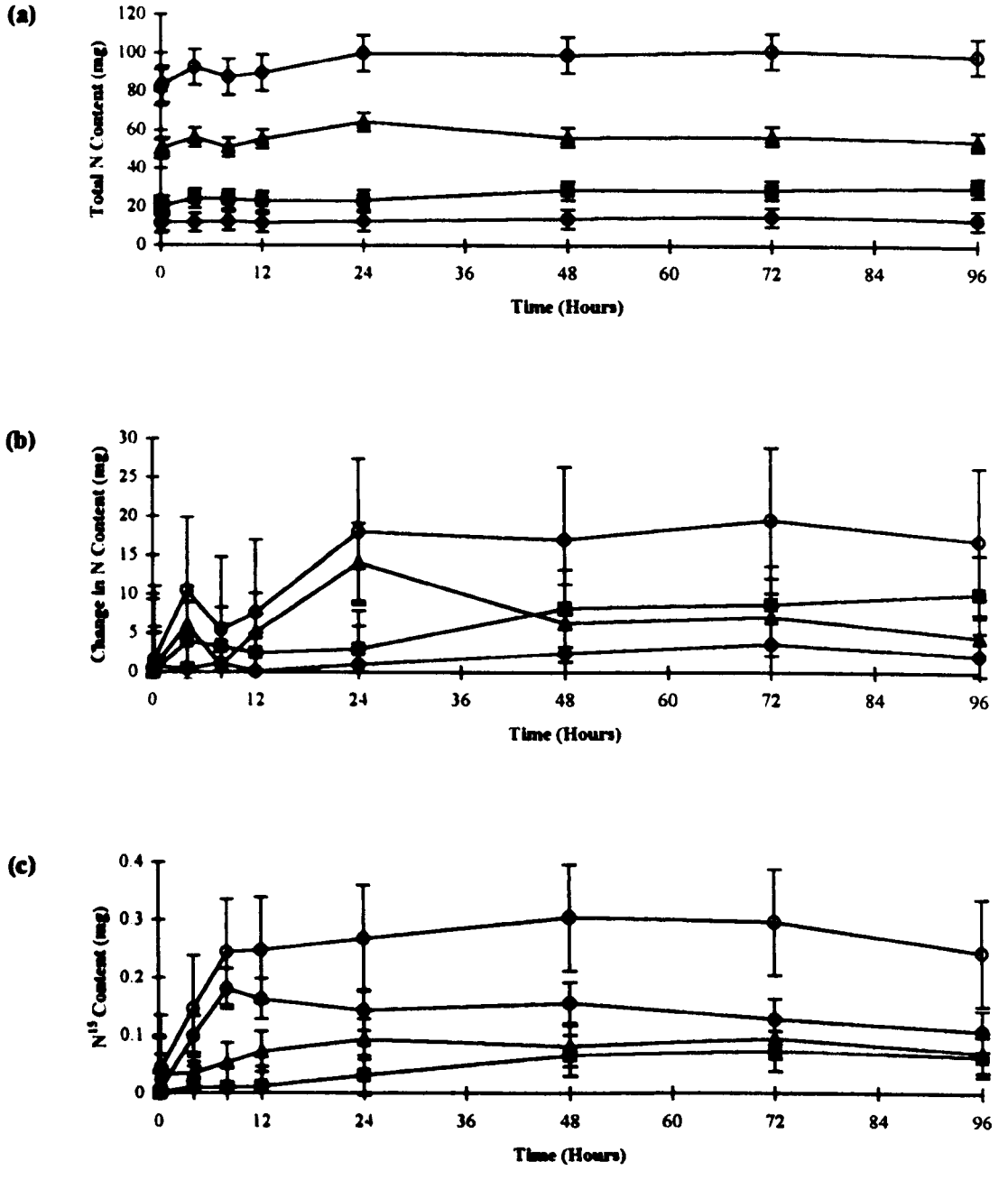


Figure 7.2 (a) The total N content (mg) of the flag leaf, ear, the rest of the plant and the total present, (b) the change in total N content (mg) and (c) the change in N^{15} content of the plant parts (mg) after the application of N^{15} labelled urea to the flag leaves of plants at anthesis. The SEDs shown have 13 df. ● flag leaf, ■ the ear, ▲ the rest of the plant, O in total.

of N present in the ear, there was no significant increase in the total amount of N present in the whole crop. The change in total N content over the same period expressed as the difference between the amount present initially and at that time (figure 7.2 (b)) shows that there was a steady uptake of N by the flag leaf and to a greater extent in the ear; but the rest of the plant showed an initial rapid uptake of N for 24 hours followed by a slow decline in the N content.

Figure 7.2 (c) shows the increase in N^{15} content of the flag leaf, ear and the rest of the plant and the total increase for the whole plant. There was an initial rapid phase of uptake by the flag leaf in the first eight hours followed by a slow transport out of the leaf up to 96 hours. Both the ear and the rest of the plant showed a slow uptake over the entire 96 hour period. The rest of the plant took up more N^{15} in the first 24 hours than the ear but in both cases significantly more N^{15} was present 96 hours after application than was present initially ($P = 0.05$, SED = 0.0330, 52 df). N^{15} was not found in the roots or the perlite/terragreen growth medium either before labelled foliar urea was applied or 96 hours after application.

7.3 DISCUSSION AND CONCLUSIONS

As illustrated in figure 7.1 (a), the losses of N^{15}-labelled urea from the leaf surface paralleled the uptake of N^{15} into the plant. This indicated that directly measured losses of urea from the surface of the flag leaves in both field and controlled environment experiments, realistically reflected the actual uptake of N into the plant. The difference between the amount of N^{15} present in the plant at the end of 96 hours and the amount present on the leaf surface initially can probably be accounted for as loss by volatilization and this was small, approximately 10 % of the amount present initially. However, variability in these data arose from variation in determining the amount of N^{15} present initially and in the amount applied. This means that these data and those illustrated in figures 7.1 (b and c) only provide an imprecise indication that N was taken up from these applications. The subsequent data confirm uptake of both labelled and unlabelled N and this is shown in figure 7.2 (b and c).

Figure 7.2 (b) and (c) suggest that the N and N^{15} were rapidly taken up by the flag leaf during the first eight to twelve hours after application, corresponding with the pattern of uptake described by Bowman and Paul (1990 a; 1990 b; 1989; 1987), Klein and Weinbaum (1985; 1984) and Weseley *et al.*, (1983) amongst others. After the initial rapid uptake, the amount of N^{15} present in the leaf declined, indicating that there was transport out of the leaf to the rest of the plant. The increase in other parts of the plant was slow and gradual, but between 12 and 24 hours there was an increase in the N^{15} content of the ear, which corresponded with a decrease in the N^{15} content of the rest of the plant. At the end of the experiment the values for the N^{15} content of the ear and the rest of the plant were similar and there may have been a cross over point beyond 96 hours after application, as the amount present in the ear continued to increase and that present in the rest of the plant was transported to the ear. It is unlikely that there was much transport away from the ear but this cannot be checked by any of the data presented here. It is therefore possible that the N was used in leaf metabolism for a short period of time before being transported to the ear.

7.4 INVESTIGATIONS INTO THE BEHAVIOUR OF FOLIARLY APPLIED UREA ON THE SURFACE OF LEAVES

Experiments were carried out under controlled conditions to examine in more detail some of the factors that might have affected uptake of foliar urea under field conditions. The aim was not to recreate field conditions but to provide a collection of uniform and representative plant material from sequential sowings, that were not over fertilized. Half life ($t_{0.5}$) was used as the measure both in the field experiments and in the experiments carried out in controlled conditions in order to compare the behaviour of different treatments. The factors compared were leaf age, leaf position, the leaf surface (adaxial or abaxial) to which urea was applied, the amount of N applied and the effects of adjuvants.

7.4.1 Materials and methods

7.4.1.1 *Production of experimental plant material*

Winter wheat *cv.* Cadenza was chosen for controlled environment experiments as it was a variety suitable for bread making (NIAB Cereals Varieties Handbook 1996), but had a low vernalization requirement allowing it to be grown in glasshouse conditions.

Two seeds were sown into a 3:1 mix of perlite and terra-green in black polythene tubes 8 cm in diameter and 40 cm long, providing an inert substrate for growth and to which a known amount of nutrients could be added. When the first leaf was fully emerged one of the seedlings was removed leaving one plant per tube for experimental use, so that there was sufficient space for the plants to grow to anthesis and beyond. The plants were watered using demineralized water and nutrients were supplied using 0.3 g of a slow release fertilizer, (Osmocote Mini 18-6-12), which was active for up to 3 months. This provided 18 % nitrogen (as 9.5 % ammonium and 8.5 % nitrate), 6 % phosphorous (as phosphate) and 12 % potassium (as water soluble potassium oxide), 4.4 % sulphur and 0.9 % calcium (as calcium sulphate). Diseases and pests were controlled with appropriate agrochemicals. The main problems were aphids, controlled using pirimicarb (Aphox, Zeneca) and powdery mildew treated with sulfur (Thiovit, PBI) and triadimefon (Bayleton, Bayer).

After sowing the plants were kept in a south facing glasshouse with supplementary lighting and heating. A 16 hour photoperiod operated and temperatures were 18 °C in the light period and 15 °C in the dark period. These temperatures were subject to ambient by +2 °C. When light levels dropped below 105 μmol m^{-2} s^{-1} the supplementary lighting of high pressure sodium discharge lamps operated providing a minimum of 126 μmol m^{-2} s^{-1} at flag leaf height, approximately 90 cm above the level of the bench. For reference, a bright sunny summer day in the UK would provide 630 μmol m^{-2} s^{-1} of light.

The plants used in the experiments were at varying stages of development and before use they were allowed to acclimatize in the controlled environment cabinet for two days.

7.4.1.2 *Controlled environment conditions*

A Saxcil growth cabinet was used to provide the controlled environment conditions. It provided a growing surface of 1.69 m^2 in size (1.3 m x 1.3 m) and was tall enough at 1.5 m to easily accommodate the plants used. The plants in the cabinet were subject to a 16 hour photoperiod, from midnight to 4 pm, with a light intensity of 300 $\mu mol\ m^{-2}\ s^{-1}$ of visible radiation from fluorescent and incandescent lamps. The temperature changed with the light conditions and was 18 °C and 15 °C respectively in the light and dark periods. The relative humidity was 70 %. Air was circulated through the cabinet at a velocity of approximately 15 $cm\ s^{-1}$ and fresh air was injected at a rate of 300 $l\ s^{-1}$.

7.4.1.3 *Track sprayer*

The foliar urea sprays were applied using a Crocus track sprayer, (Crocus, Stockport, Cheshire). This track sprayer comprised a horizontal boom 0.55 m wide, fitted with two Lurmark 02-F110 110° flat fan nozzles (orange) 0.5 m apart. The spray pattern was comparable to that from the boom of a standard tractor mounted or back pack sprayer. The sprayer was pressurised by a CO_2 cylinder, set at 2 bar to produce a fine spray and therefore a greater coverage of the plant material. The effective area covered by the sprayer was 0.75 m^2 (1.5 m long x 0.5 m wide) which allowed a maximum of seven separate individual plants or targets to be sprayed at variable heights at one time, or up to 20 detached leaves or targets placed on a single sheet of perspex 0.6 m x 0.4 m in size, raised 0.6 m above the ground. The speed at which the spray boom was operated could be varied but a standard speed of 1.000 $m\ s^{-1}$ (3.6 $km\ h^{-1}$) was used to maintain coverage of the plant material. A standard urea solution containing 15 kg N ha^{-1} in 200 $l\ ha^{-1}$ of water was applied, producing a coverage of 0.326 mg cm^{-2} of urea (0.15 mg cm^{-2} of N).

Foliar urea was applied to a single leaf of a plant that had been laid out along a strip of perspex 5 cm x 25 cm in size. The perspex strip was held using a retort stand and clamp and set at the height of the ligule of the leaf to be sprayed. The leaf was carefully laid out along the perspex strip and the tip of the leaf secured to the perspex using a piece of electrical tape which could then be easily removed. The whole area of the leaf could then be sprayed. After spraying, the spray deposits were allowed to dry for approximately one minute before the tape was carefully removed and the leaf either replaced in its previous position or removed using scissors and tweezers, and washed to remove any urea deposited onto it.

To avoid contamination between spray treatments and replicates, all the apparatus used was carefully washed and dried between applications. The spray mechanism was flushed out with water to clean the holding tank, pipes and nozzles after each experiment. Each spray application included a control to measure the amount of urea deposited, a 2 cm x 21 cm strip of acetate was used and treated in an identical manner to the sprayed leaves.

The sprayer was calibrated weekly by collecting the output of each spray nozzle in a measuring cylinder, to ensure that the correct volume for the nozzle type and the operating pressure used was delivered (0.698 l min^{-1}).

7.4.1.4 *Treatments applied*

An experiment consisted of a single treatment or variable to be examined, with three replicates, sprayed separately. A replicate contained up to six separate plants and a control, placed randomly, one plant or leaf representing one sample time, when the leaf was removed from the plant using scissors and tweezers and any urea present on the leaf surface washed off in 200 ml of 0.1 % Triton X-100 solution for ten minutes. In selecting plants for each replicate, care was taken to ensure that the plants were at the same growth stage, and that the leaves to be sprayed were of a similar size. After the treatments had been applied the plants were placed in the Saxcil growth cabinet, the three replicates arranged

separately. The amount of urea present in the washing solutions was determined by the diacetyl monoxime assay, (section 6.1.3).

The variables tested under controlled environment conditions used $t_{0.5}$ as an indicator of differences between treatments and considered the effect of leaf age, whether foliar urea was applied to the adaxial or abaxial leaf surface, the amount of N applied (kg ha^{-1}) and the effect of adjuvants.

7.4.2 Confirmatory experiments

Additional experiments were carried out to determine whether there was excessive loss by evaporation or volatilization of foliar urea when applied in controlled environment conditions and also if the size of the target significantly affected the amount of urea deposited per unit area.

7.4.2.1 *Loss from an artificial system*

Foliar urea was applied to strips of acetate (2 cm x 21 cm in size), using the track sprayer; these were then placed in the Saxcil growth cabinets and measurements of the amount of urea present on the strips were made over a 96 hour period. Table 7.1 shows that there were no significant differences in the amount of urea present at each time point and no significant changes occurred over the 96 hours. It is therefore unlikely that there was a significant loss of urea by either evaporation or volatilization in controlled environment conditions.

Table 7.1 The amount of urea (mg cm^{-2}) present on strips of acetate kept in controlled environment conditions for 96 hours. The SED has 14 df.

Time	**0**	**4**	**8**	**24**	**32**	**48**	**72**	**96**	**SED**
Urea	0.234	0.226	0.232	0.247	0.251	0.224	0.223	0.236	0.0176

7.4.2.2 *Size of target*

Foliar urea was applied using the track sprayer to a number of artificial targets of acetate strips, ranging in size from 2.5 to 84 cm^2. Table 7.2 indicates that there was no significant difference in the amount of urea intercepted by each of the differently sized targets and this was also unaffected by the width or length of the targets.

Table 7.2 The amount of urea (mg cm^{-2}) deposited onto the surface of differently sized artificial targets of acetate from applications of foliar urea in controlled conditions.

	Length (cm)			
Width (cm)	**5**	**10**	**15**	**21**
0.5	0.263	0.256	0.268	0.268
1	0.236	0.266	0.275	0.267
2	0.252	0.273	0.224	0.269
4	0.291	0.291	0.275	0.250

For comparisons between different widths SED = 0.0122 (24 df), between lengths SED = 0.0137 (6 df), between widths and lengths SED = 0.0252 (28 df) except when comparing between means of the same length SED = 0.0244 (24 df).

7.4.3 **Initial Experiments**

The aim of these experiments was to determine the dynamics of loss of urea from the surface of a leaf. The first experiments carried out in controlled conditions revealed that the loss of urea from the adaxial surface of a flag leaf at anthesis potentially followed an exponential curve, r^2= 0.509 (SED= 0.0101, 6 df), see figure 7.3. The half life ($t_{0.5}$) was calculated as 38.89 hours for half of the urea present initially to be lost from the surface of the leaf.

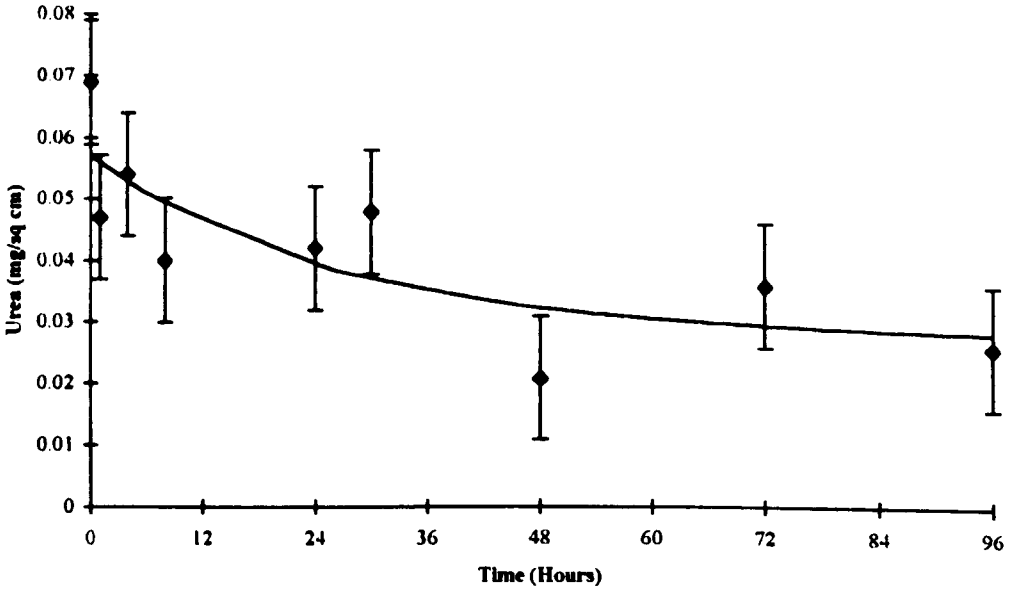


Figure 7.3 An initial experiment showing the loss from the surface of the adaxial surface of flag leaves at anthesis. The fitted curve is an exponential, $r^2 = 0.509$ and the SEDs shown have 6 df.

The results obtained from subsequent experiments described in the following sections do not conform to a specific relationship described by a mathematical equation. This was mostly caused by the large variation inherent in the data and therefore exponential curves were fitted with caution, $t_{0.5}$ was only calculated when the data could be described in this manner and was used to indicate treatment differences.

7.5 LEAF AGE

7.5.1 **Flag leaf age**

Foliar urea was applied to the adaxial surface of a flag leaf immediately after full leaf emergence and then on five subsequent occasions, measured as days after full emergence, up to the end of anthesis. The amount of urea lost from the leaf surface was monitored over a 72 hour period.

Figures 7.4 (a-f) illustrate the mean patterns of loss of urea from the leaf surface. Measured over 72 hours all treatments showed a small decline in the amount of urea present. $t_{0.5}$ was calculated for all leaf ages with the exception of the newly emerged leaf (0 days) figure 7.4 (a) and 27 days after emergence (e) when an exponential curve could not be fitted and there appeared to be no relationship between the data points. Table 7.3 shows that there may have been a reduction in $t_{0.5}$ as the age of the leaf increased.

Table 7.3 The half life (hours) for the loss of urea from the adaxial surface of flag leaves of different ages, from full leaf emergence to 34 days afterwards.

Days from full leaf emergence	$t_{0.5}$
0	-
+ 8	48.6
+ 13	70.0
+ 21	24.3
+ 27	-
+ 34	18.0
SED (8 df)	10.55

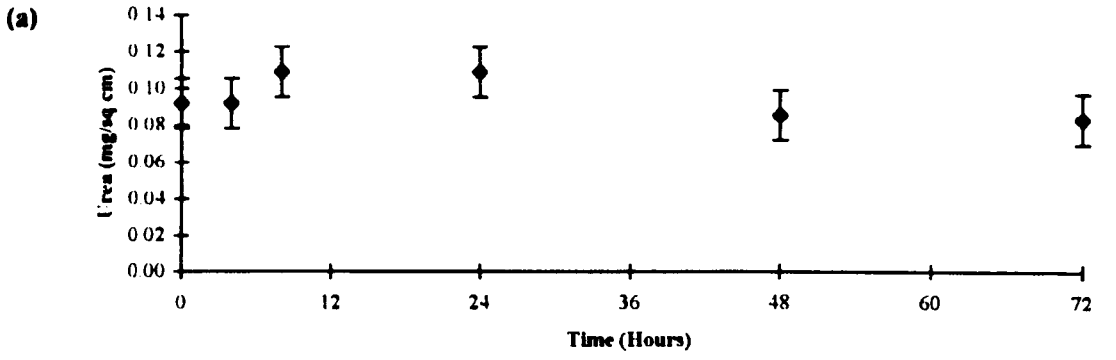
7.5.2 Age of flag -2

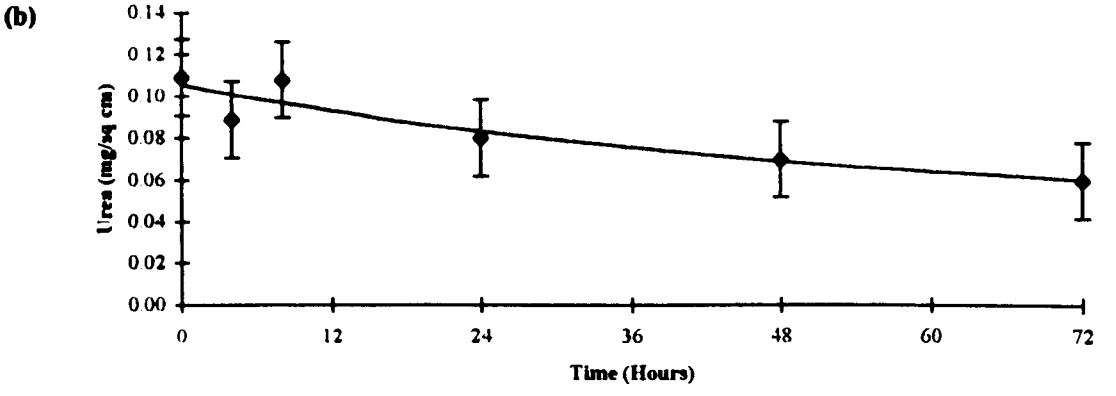
Foliar urea was applied to the adaxial surface of the leaf flag-2 immediately after full leaf emergence and then on five subsequent occasions, measured as days after full emergence, up to the end of anthesis. This provided a contrasting leaf to the flag leaf on which to study the dynamics of loss of urea. The amount of urea lost from the leaf surface was monitored over a 72 hour period. Table 7.4 shows $t_{0.5}$ calculated when exponential curves could be used to describe the data.

Table 7.4 The half life (hours) for the loss of urea from the adaxial surface of the leaf flag - 2 at different ages, from full leaf emergence to 33 days afterwards.

Days from full leaf emergence	$t_{0.5}$
0	-
+ 7	75.2
+ 13	-
+ 20	27.5
+ 26	11.8
+ 33	48.3
SED (8 df)	22.34

The data for the three replicates were very variable, at full leaf emergence and for + 13 days after full leaf emergence an exponential curve could not be fitted to the data. There was no significant difference in $t_{0.5}$ with respect to leaf age. Figures 7.5 (a-f) illustrate the loss of urea from the leaf surface and shows that there was a small decline in the amount present over 72 hours.





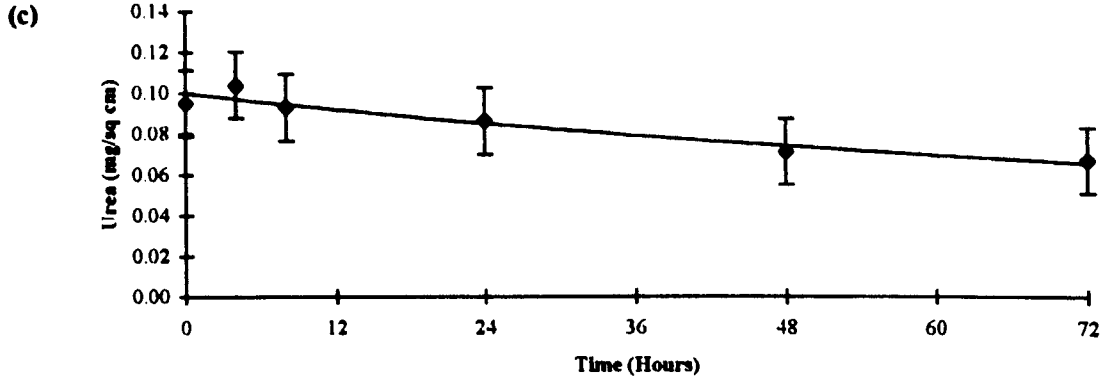
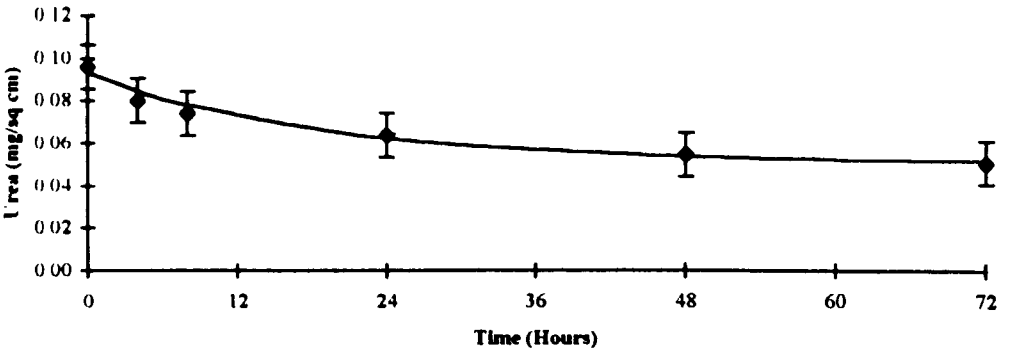
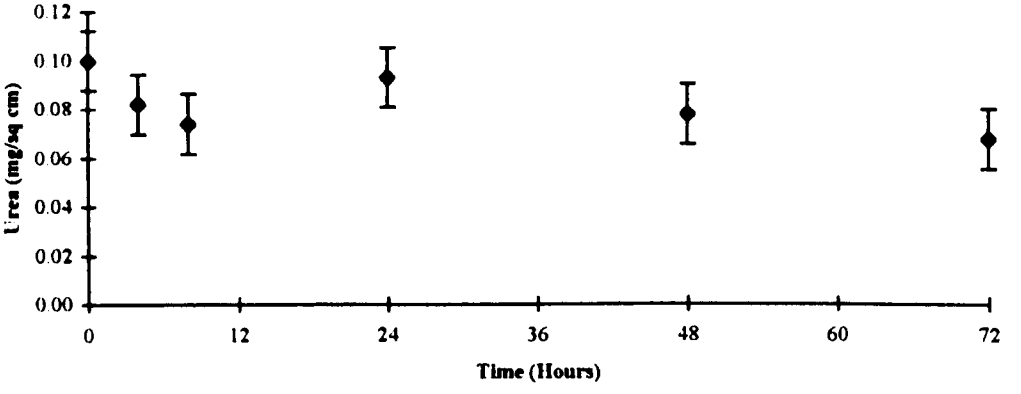


Figure 7.4 (a-c) The loss from the adaxial surface of flag leaves (a) 0 days, (b) 8 days and (c) 13 days from full leaf emergence, measured over 72 hours. Where exponential curves could be fitted, r^2 = (b) 0.756 and (c) 0.864. The SEDs shown have 10 df.

(d)



(e)



(f)

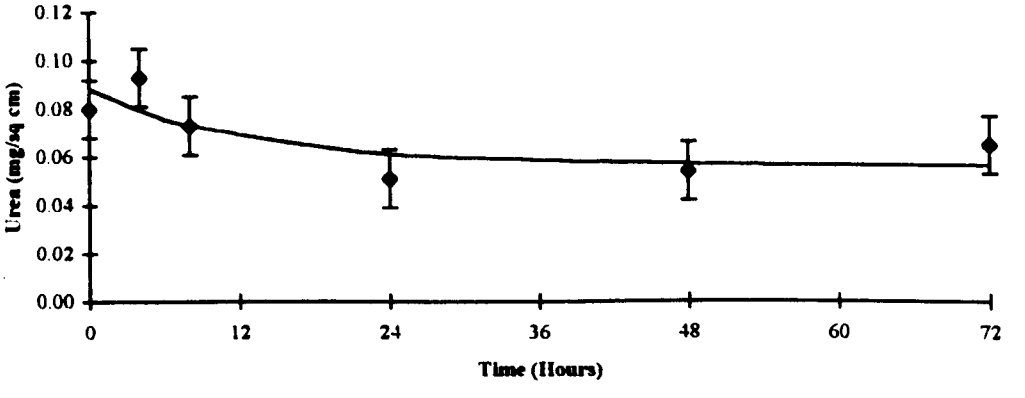


Figure 7.4 (d-f) The loss from the adaxial surface of flag leaves (d) 21 days, (e) 27 days and (f) 34 days from full leaf emergence, measured over 72 hours. Where exponential curves could be fitted r^2 = (d) 0.959 (f) 0.435 respectively. The SEDs shown have 10 df.

7.6 ADDITIONAL VARIABLES

7.6.1 **Flag leaf surface**

Franke (1967) showed that foliarly applied compounds were taken up more rapidly from the lower or abaxial leaf surface than from the adaxial surface. Experiments carried out on flag leaves at full flag leaf emergence and anthesis compared the half lives obtained for the loss of urea from the adaxial and abaxial leaf surfaces.

Table 7.5 The half life (hours) for loss of urea from the adaxial and abaxial surfaces of the flag leaf at different stages of growth, flag leaf emergence and at anthesis.

Growth Stage	$t_{0.5}$
Flag leaf emergence - Adaxial	33.7
- Abaxial	26.1
Anthesis - Adaxial	35.6
- Abaxial	36.8
SED (8 df)	28.82

The surface of the leaf to which foliar urea was applied did not significantly affect the time for $t_{0.5}$ and this was unaffected by the growth stage of the plant. Figures 7.6 (a-d) show that urea was lost from the leaf surface, the data fitted more reliably to exponential curves.

7.6.2 **Amount of N applied**

Varying amounts of N from 7.5 to 120 kg N ha^{-1} as multiple, successive applications of 15 kg N ha^{-1} in 200 l ha^{-1} of water, were applied to the adaxial surface of flag leaves of plants at anthesis. Figures 7.7 (a-f) show the loss from the surface of the leaf over 72 hours and table 7.6 the calculated half lives.

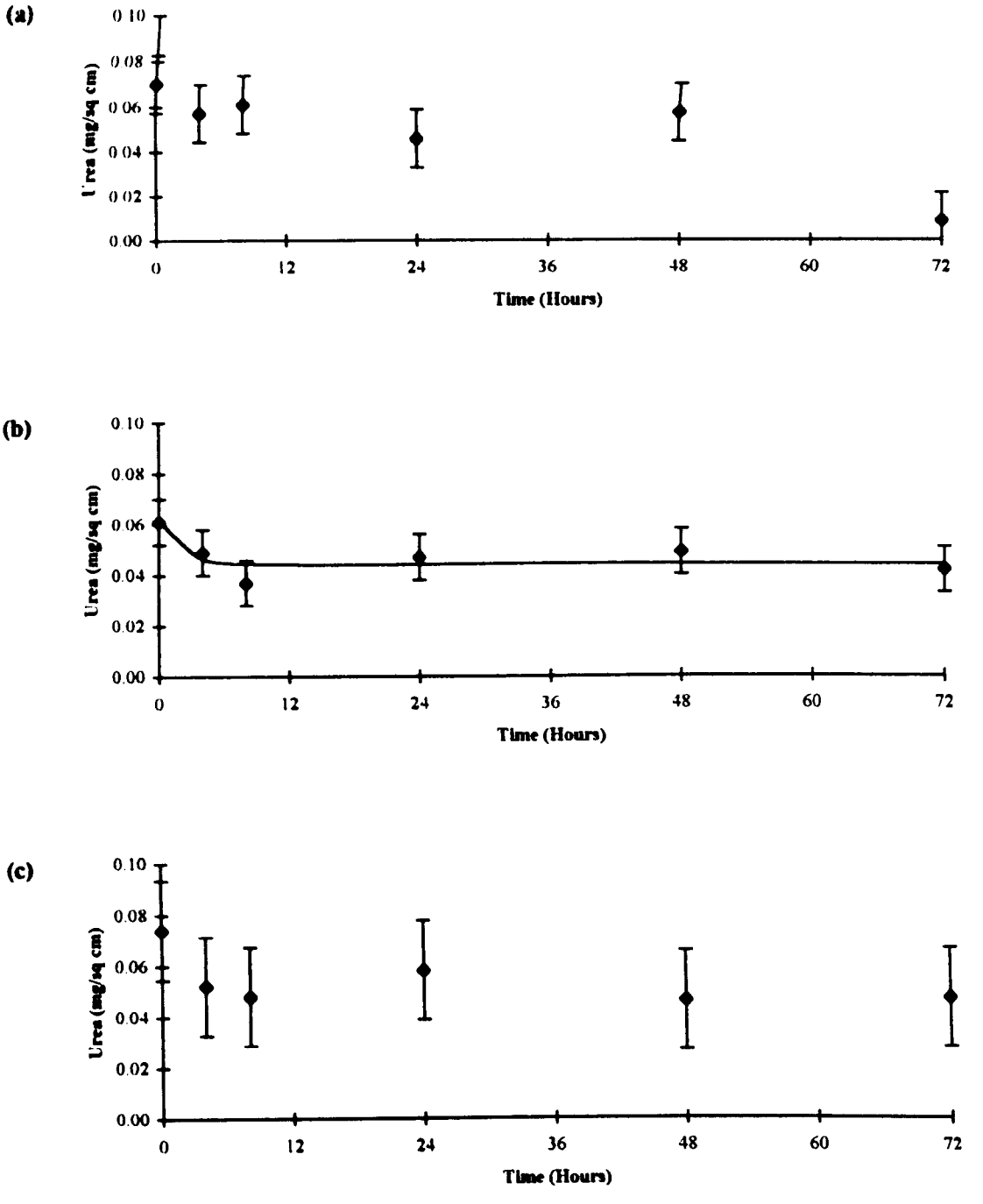


Figure 7.5 (a-c) The loss from the adaxial surface of the leaf flag -2 (a) 0 days, (b) 7 days and (c) 13 days from full leaf emergence, measured over 72 hours. Where exponential curves could be fitted r^2 = (b) 0.500. The SEDs shown have 10 df.

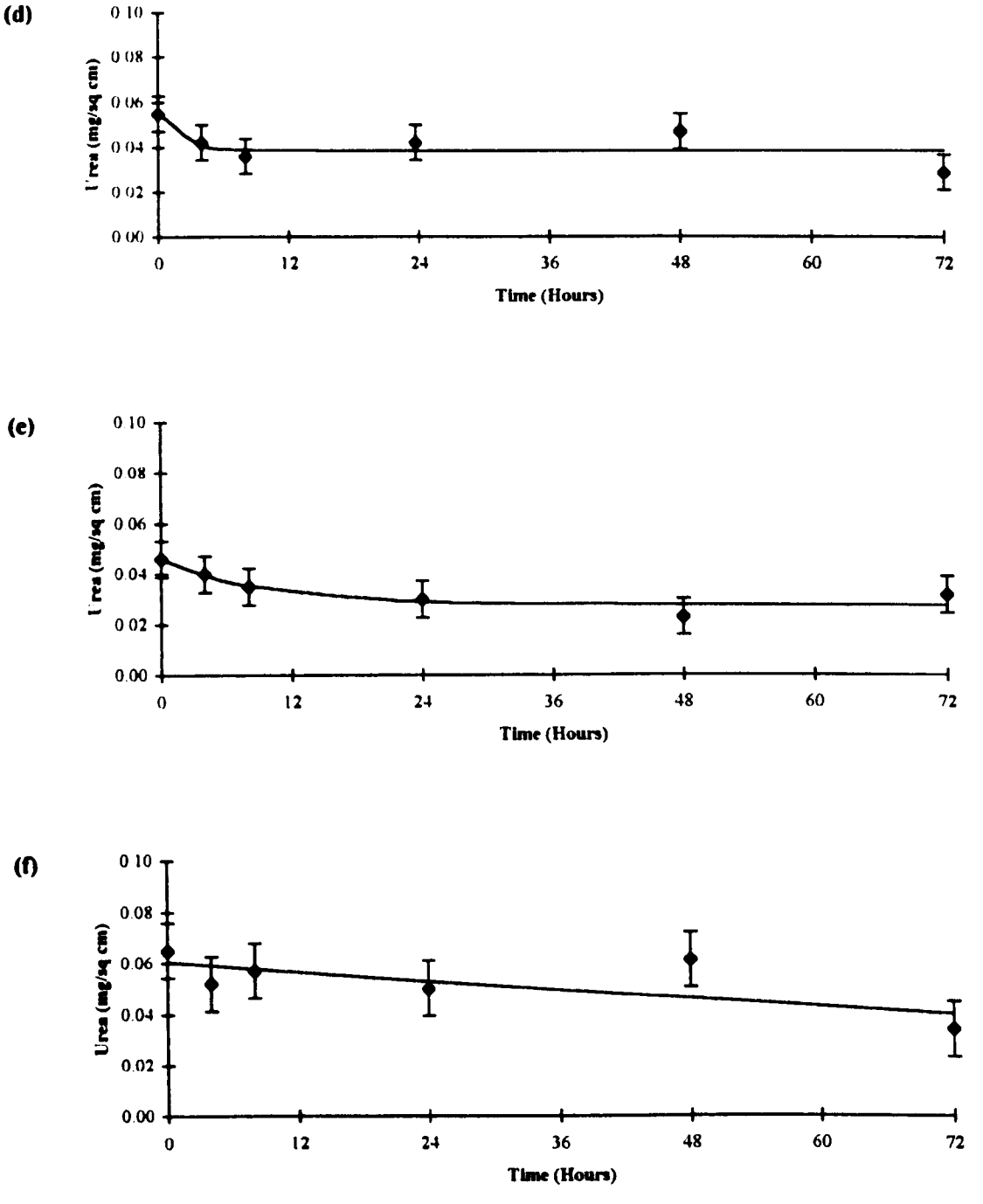
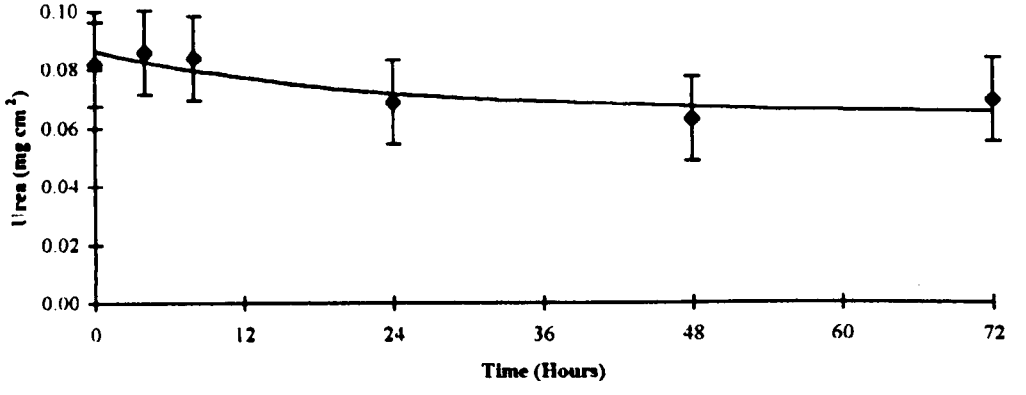


Figure 7.5 (d-f) The loss from the adaxial surface of the leaf flag -2 (d) 20 days, (e) 26 days and (f) 33 days from full leaf emergence, measured over 72 hours. Where exponential curves could be fitted r^2 = (d) 0.231, (e) 0.779 and (f) 0.569 respectively. The SEDs shown have 10 df.

(a)



(b)

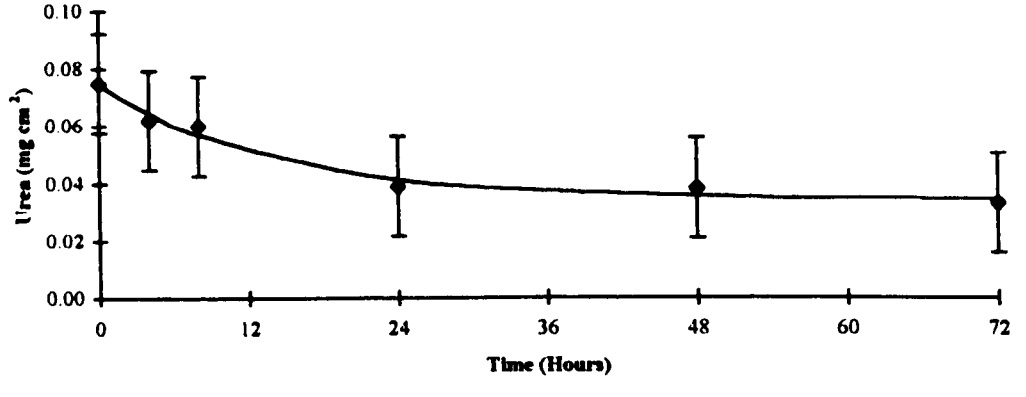
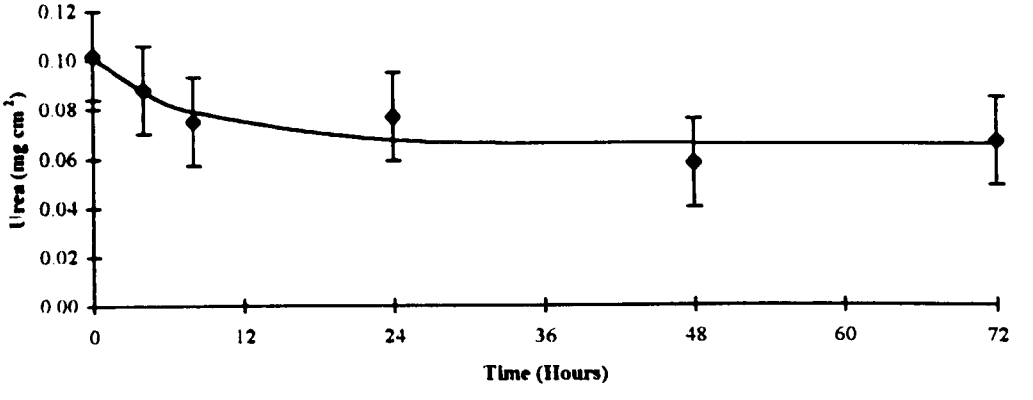


Figure 7.6 (a) The loss from the adaxial surface and (b) from the abaxial surface of flag leaves at flag leaf emergence measured over 72 hours. The curves fitted are exponential and have r^2 values of 0.657 and 0.965 respectively. The SEDs shown have 10 df.

(c)



(d)

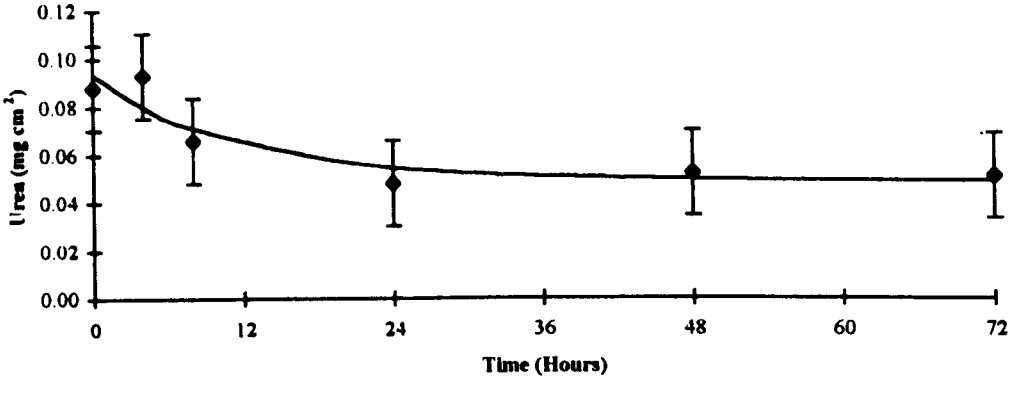


Figure 7.6 (c) The loss from the adaxial surface and (d) from the abaxial surface of flag leaves at anthesis measured over 72 hours. The curves fitted are exponential and have r^2 values of 0.767 and 0.773 respectively. The SEDs shown have 10 df.

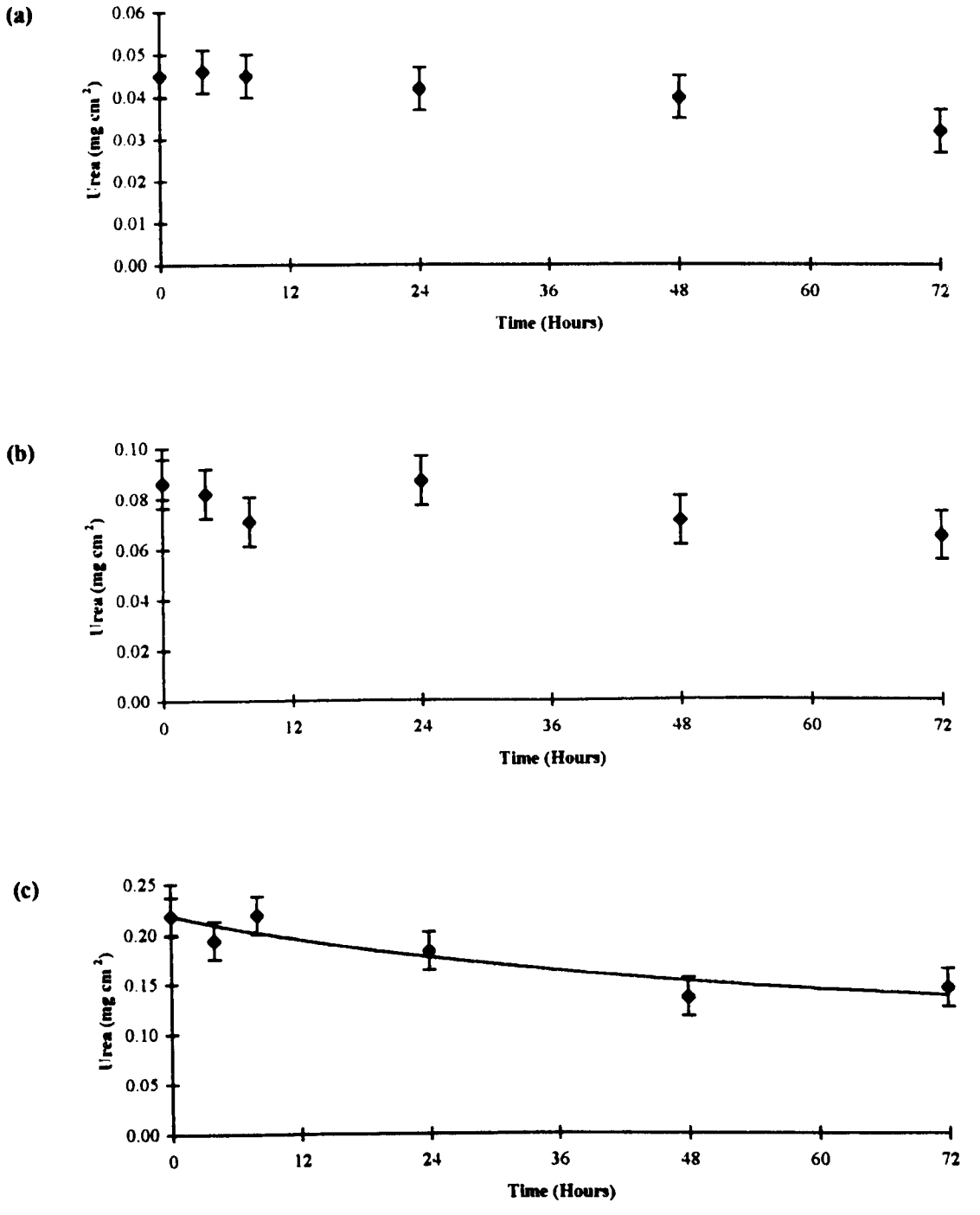
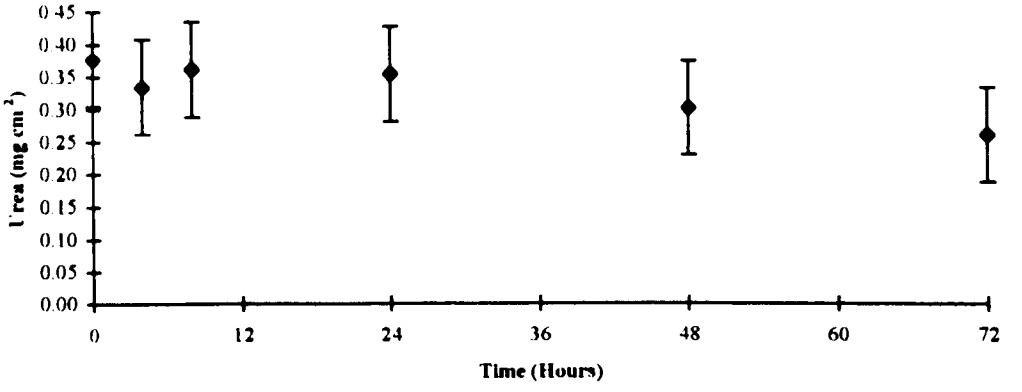
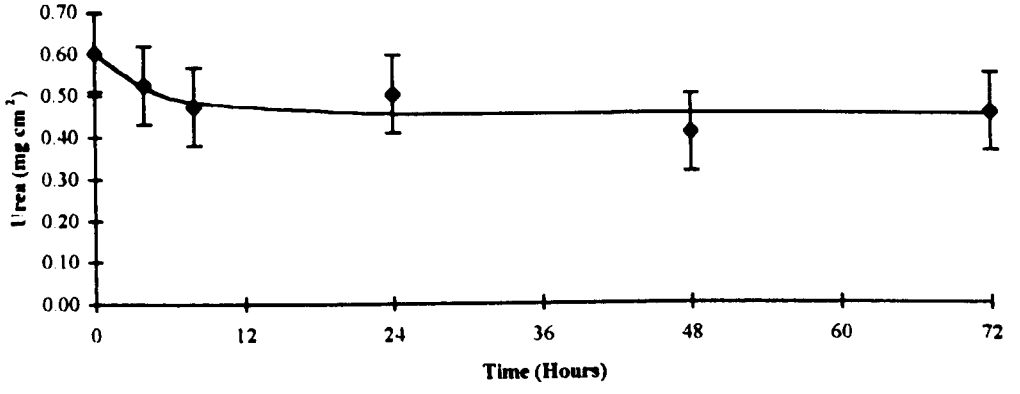


Figure 7.7 (a-c) The loss from the adaxial surface of the flag leaf at anthesis receiving (a) 7.5 kg N ha^{-1}, (b) 15 kg N ha^{-1} and (c) 30 kg N ha^{-1} measured over 72 hours. Where exponential curves could be fitted r^2 = (c) 0.762 respectively. The SEDs shown have 10 df.

(d)



(e)



(f)

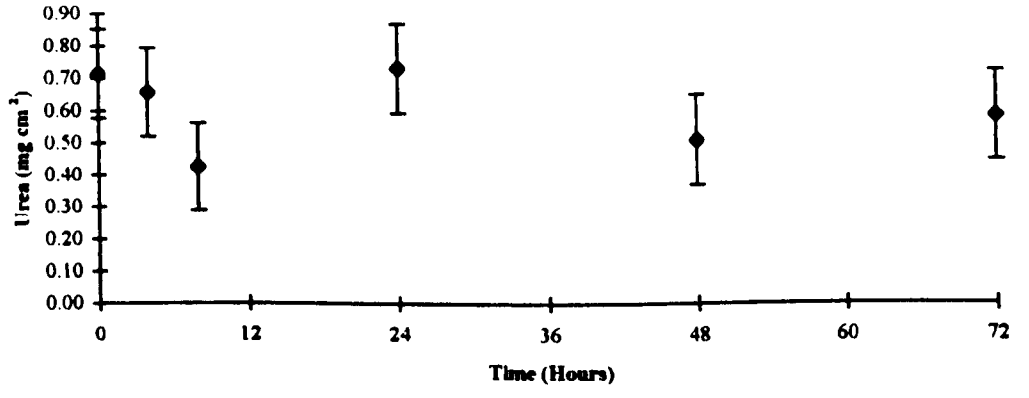


Figure 7.7 (d-f) The loss from the adaxial surface of the flag leaf at anthesis receiving (d) 60 kg N ha^{-1}, (e) 90 kg N ha^{-1} and (f) 120 kg N ha^{-1} measured over 72 hours. Where exponential curves could be fitted r^2 = (e) 0.672. The SEDs shown have 10 df.

Table 7.6 The half life (hours) for the loss of urea from the adaxial surface of a flag leaf of plants at anthesis when different amounts of N were applied.

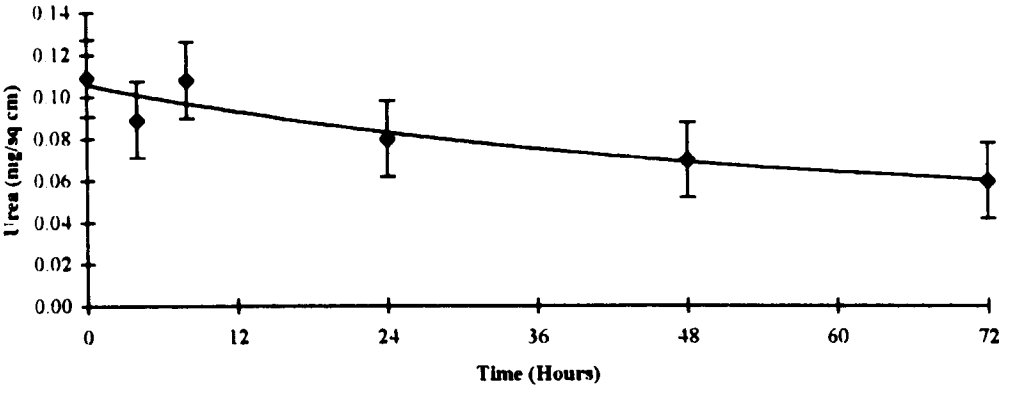
N kg ha^{-1}	$t_{0.5}$
7.5	-
15	-
30	69.9
60	-
90	37.3
120	-
SED (4 df)	25.29

As the variability within the data was so large and exponential curves could only be fitted to the data for 30 and 90 kg N ha^{-1} it was not possible to draw any conclusions from the data for $t_{0.5}$.

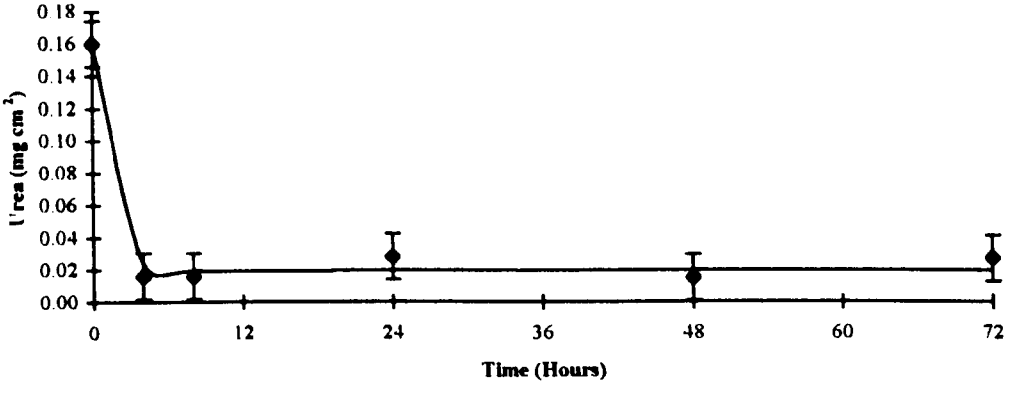
7.6.3 The use of adjuvants

The adjuvants that had been applied to the field experiment at IACR-Rothamsted in 1995 were also tested in controlled environment conditions with the same timings of application. The spreader Silwet L-77 was applied just prior to ear emergence and at anthesis, Spray-Fix (a sticker) and the penetrant LI-700 were also applied prior to ear emergence as a 0.1 % solution with 15 kg N ha^{-1} in 200 l ha^{-1} water as foliar urea. Table 7.7 shows $t_{0.5}$ for these treatments and figure 7.8 (a - e) the loss of urea over 72 hours.

(a)



(b)



(c)

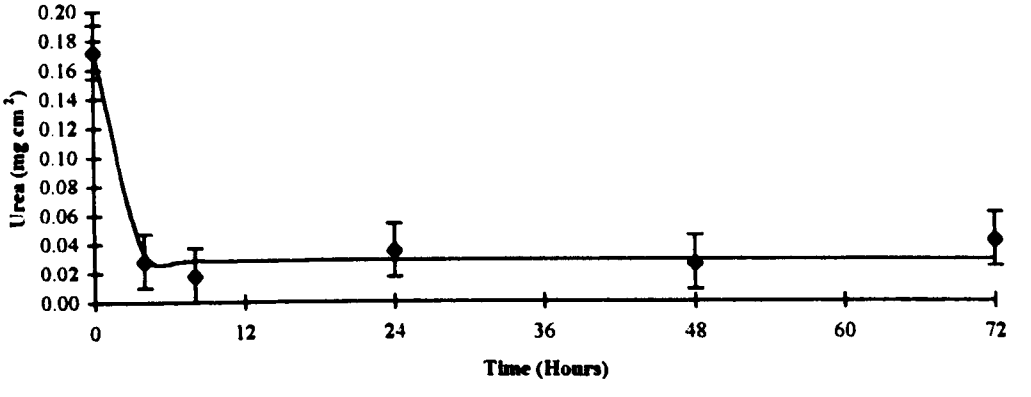
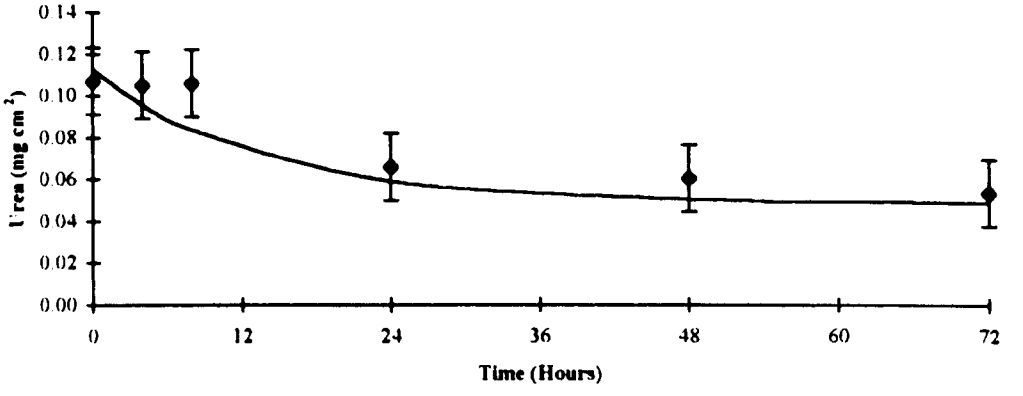


Figure 7.8 (a-c) The loss from the adaxial surface of flag leaves receiving (a) foliar urea without an adjuvant at ear emergence, (b) with 0.1 % Silwet L-77 at ear emergence and (c) at anthesis measured over 72 hours. Where exponential curves could be fitted r^2 = (a) 0.756, (b) 0.977 and (c) 0.964. The SEDs shown have 10 df.

(d)



(e)

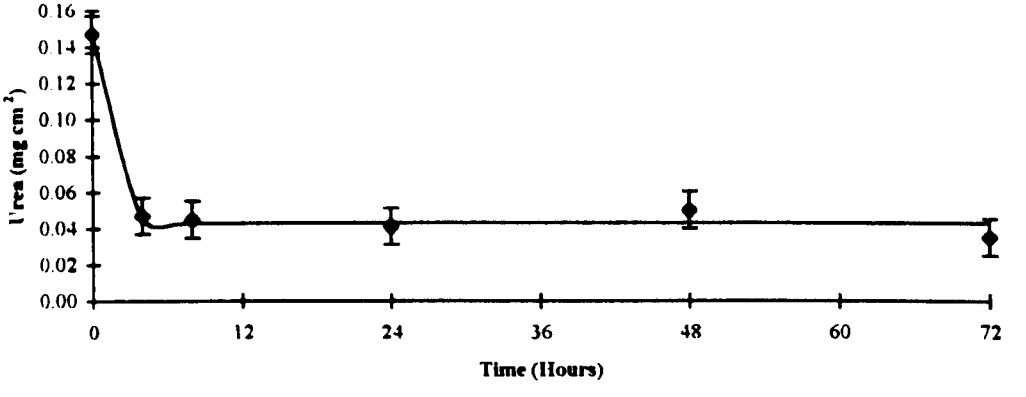


Figure 7.8 (d-e) The loss from the adaxial surface of flag leaves receiving (d) foliar urea with 0.1 % Spray-Fix at ear emergence and (e) foliar urea with 0.1 % LI-700 at ear emergence measured over 72 hours. Where exponential curves could be fitted r^2 = (d) 0.890 and (e) 0.978. The SEDs shown have 10 df.

Table 7.7 The half life (hours) for the loss of urea from the adaxial surface of a flag leaf receiving foliar urea with a 0.1 % solution of one of three adjuvants.

Adjuvant	$t_{0.5}$
no adjuvant	48.6
Silwet L-77 at ear emergence	1.0
Silwet L-77 at anthesis	1.4
Spray-Fix	44.4
LI-700	1.5
SED (8 df)	8.52

Both Silwet L-77 and LI-700 significantly reduced $t_{0.5}$ compared to when an adjuvant was not used, but when Spray-Fix was applied with the foliar urea $t_{0.5}$ was not affected compared to when foliar urea was applied without an adjuvant. The pattern of loss described by all these treatments appeared to conform to an exponential curve.

7.7 DISCUSSION AND CONCLUSIONS

The amount of urea deposited onto both the leaves and the artificial acetate targets (mg urea cm^{-2}) was less than the amount delivered from the nozzles as some drifted from the target through the turbulence created by the movement of the boom (Grayson and McCarthy, 1987) and by the evaporation of the smaller spray droplets before impaction onto the target (Matthews, 1982). The spray nozzle used in these experiments produced a finer spray than the nozzles used in the field applications, in order to increase the coverage of the plant material, so there was a greater likelihood of the smaller droplets evaporating before impact. The difference in the amount of urea deposited onto the surface of the acetate strips and the leaves could possibly be accounted for by the difference in the nature of the surface of each, with the acetate reducing the amount lost by bounce off.

Measuring the amount of N present on the surface of the leaves of crops to which foliar urea had been applied had proved to be an accurate and easy way of determining the amount of urea deposited onto the crop and the dynamics of the loss of urea from the crop surface under field conditions (Chapter 6). Measurements, primarily on the flag leaf, showed that the loss was consistently exponential (section 6.4.8). The inherent errors within this method had also been consistently small in the field and the calculation of half lives for the loss of urea from the surface of the flag leaf provided a simple method of comparing the effectiveness of different treatments. This method therefore appeared sufficiently reliable for use in the less exacting conditions of controlled environment, but this was not the case. Unfortunately the data produced using this technique were not conclusive, largely due to the variation within the data sets. This was probably partially related to the differences in the initial amounts of N deposited onto the leaves which may have been affected by the size of the leaf itself. Although this was not initially thought to be a factor from the results described in 7.4.2.2, subjective observations based on the area of the leaves suggested that smaller leaves may have intercepted less urea per unit area of leaf than their bigger counterparts, possibly because they tended to be narrower. However, it is also possible that the experimental techniques employed in controlled environment conditions were also a factor.

The initial experiments (section 7.4.3) showed that the loss of urea from the adaxial surface of a flag leaf at anthesis conformed reasonably to the exponential curve expected from the field experiments, but compared to field measurements, the half life ($t_{0.5}$) was quite long at 38.9 hours, even though less N was applied. The controlled conditions may, therefore have been less conducive to the loss of urea by volatilization or evaporation and this was also suggested by the experiments described in section 7.4.2.1, which indicated that there were not excessive losses by either evaporation or volatilization from the artificial targets used.

Subsequent experiments examined the effect of the age of the flag leaf and also the position on the plant (leaf flag -2) on the dynamics of loss from the surface of the flag leaf. Despite using three replicates, the data obtained were very variable, particularly for measurements

made on the flag leaf immediately after full leaf emergence, 27 days afterwards and 13 days after full emergence of flag-2. On these occasions the data were not described by an exponential curve; very little urea appeared to be lost. Since flag -2 is developmentally older than the flag leaf, the leaf cuticle thickens with increasing leaf age (Franke, 1986), $t_{0.5}$ would be expected to be greater than for the flag leaf. In fact there were no real differences, and this may be a function of the reduced amount of urea present initially on the leaf surface, something that from the experiment described in section 7.4.2.2, was not expected. However Grayson and McCarthy (1987) amongst others, have stated that deposition onto field grown crops was related not only to the angle and position of the target within the canopy but also to its surface area. Therefore these results are somewhat inconclusive.

Where data sets are not described by an exponential curve and only a small amount of urea appeared to be lost from the leaf surface over a 72 hour period, there may have indeed only been limited uptake or volatilization and evaporative loss. However, what may be more likely is that the amounts of urea deposited onto the individual leaves were sufficiently different to obscure any changes that might have been caused by uptake.

The results obtained for the loss of urea from the adaxial and abaxial leaf surfaces were more accurate and produced analyzable exponential curves. $t_{0.5}$ do not indicate any differences in the rate of urea uptake between the leaf surfaces. There may have been a slight reduction in $t_{0.5}$ for the abaxial (lower) side of the leaf at flag leaf emergence, corresponding to reports by Cain (1956) and Franke (1967) of increased uptake, but this was not shown conclusively.

Increasing the amount of N applied increased $t_{0.5}$ but the differences were not significant, again due to the large variability within the data. As the initial amount of urea-N present on the leaf surface increased, the amount lost over 72 hours also increased, in proportion to the amount applied, up to a maximum of 60 kg N ha^{-1}. This could be associated with an increase in the rate of uptake from progressively larger amounts of urea-N present initially,

a greater concentration gradient across the leaf surface may facilitate more rapid uptake by diffusion. For 90 and 120 kg N ha^{-1} the amount deposited initially was not proportional to the amount applied, probably because there was run off due to the large volume of liquid on the leaf surface. There may also have been increased evaporation and volatilization. In these cases only a small amount of urea was lost, suggesting that the leaf surface was so saturated with urea that the rate of uptake was actually reduced.

Adjuvants had a profound effect upon the dynamics of loss from the leaf surface. Leaves initially retained almost twice the amount of urea when standard rates of N were applied with the spreader Silwet L-77 (at ear emergence or anthesis) or with the penetrant LI-700 (at ear emergence). With both adjuvants, most of the urea ultimately "lost" from the leaf surface disappeared within the first four hours and little was "lost" subsequently, ($t_{0.5} < 1.5$ hours). There was only a slight increase in urea deposition when the sticker Spray-Fix was used and it took eight hours for a significant amount of urea to disappear from the leaf surface. Except with Spray-Fix it appears that uptake was rapid, promoted by the presence of the adjuvants (as would be expected from the reports in the literature), or, that the adjuvants increased the losses incurred through volatilization and evaporation, which is unlikely as evaporative loss tends to be reduced by the presence of an adjuvant. These results contradict both the findings of the field experiments and the fact that urea is not charged (adjuvants being promoters for the uptake of charged compounds). However, they are confirmed by examples in the literature of the beneficial affects of both Silwet L-77 and LI-700 on deposition and uptake of agrochemicals (*e.g.* Green *et al.*, 1993; Omokawa *et al.*, 1993).

Chapter 8: DISCUSSION AND CONCLUSIONS

The title of this study, 'Uptake and utilization of nitrogen applied to the foliage of winter wheat', embraced the use of foliar urea for the maintenance of the green area of Canopy Managed crops and related this to changes in grain yield and quality. It allowed detailed examination of the behaviour of N sourced from foliar urea applications both on the surface of the plant and within it, from the time the N left the spray boom to when it reached its final destination within the crop.

This discussion will consider the efficiency with which N was taken up by winter wheat crops from foliar urea applications when applied as late-N treatments to Canopy Managed (GAI 5) crops. The effect that this late-N has upon the duration of GAI of crop canopies and also upon grain yield and the quality of the grain produced will also be discussed.

8.1 N UPTAKE AND UTILIZATION FROM APPLICATIONS OF FOLIAR UREA

8.1.1 The efficiency of N uptake and the factors affecting it

The field experiments at IACR-Rothamsted and Sutton Bonington yielded information on the total N uptake and recovery by the crops, the partitioning of this N to the grain at harvest; and the percentage recovery of N from foliar urea applications. They also allowed examination of the amount of N deposited from foliar urea applications, the dynamics of loss from the leaf surface and uptake from this. Studies in controlled environment conditions allowed a more detailed examination of the factors that may have affected uptake and the use of N^{15} labelled urea to determine the fate of N within the plant and the proportion of N lost by volatilization.

Foliar urea applications to GAI 5 crops produced a distinct pattern of deposition with more than half of the applied N deposited onto the top part of the canopy, the flag leaf, flag -1

and, when present, the ear. In the variety Mercia, flag -1 is usually greater in size than the flag leaf, although this was the case in this study, there were actually no significant differences in the area of these two leaves. The experiment described in 7.4.2.2 indicated that under controlled environment conditions the size of the target (artificial) was not important in determining the amount of N deposited onto it per unit area. If this was then applied to field conditions, irrespective of size, the leaf at top of the canopy, the flag leaf, would intercept the greatest amount of N, but this was not always the case (figure 6.3). Flag -1 had a greater amount of N deposited onto it than the flag leaf on five occasions (figure 6.3 a, e, f, g and h), which suggested that determining the amount of N deposited was more complex than simply leaf position within the canopy. Deposition could also be affected by the orientation of the leaves, vertically or horizontally, the nature of the foliar urea application made, and the size of the crop canopy to which it was applied, suggesting that leaf size may also be important.

Direct uptake of N by the individual organs could not usually be shown over 96 hours by measuring the N content (figure 6.4). However the variation in the N content of the flag leaf (figure 6.6) suggests that N was taken up by this leaf and then transported away from it, possibly to the ear for applications made at anthesis. This was supported by the data obtained from the experiment using N^{15} labelled urea. Figure 7.2 (b and c) show the initial rapid uptake by the flag leaf, with subsequent increases in the N and N^{15} content of the rest of the plant which may indicate transport from the flag leaf to these plant parts. As the largest amounts of N were deposited onto the ear, flag leaf and flag -1 under field conditions it is probable that although it could not be measured definitively, these organs were also the most important organs for the uptake of N.

Chen and Ching (1988) showed that N taken up by barley from applications of foliar urea was taken up as the whole urea molecule and not hydrolysed to ammonium and carbon dioxide before uptake, this would require a large amount of ureolytic enzymes to be present on the leaf surface for uptake to be as rapid as has been reported. Bowman and Paul (1990 a), found that 35-55 % of the applied urea had been taken up in the first 12 hours.

Bowman *et al.*, (1987) suggested that there was little urease activity on the leaf surface, but the presence of urea on the leaf surface stimulates the production of urease enzymes (Hoult and McGarity, 1989). Several studies have recorded a considerable increase in the urea content of the leaf immediately after the application of foliar urea and in the hours following it, for example, Turley and Ching (1986 b), Chen and Ching (1988) and Bowman and Paul (1990 a). This therefore supports the conclusion that urea was taken up by the plant as a whole molecule and only then was it hydrolysed to ammonium *in vivo*. However, the change in the urea content of the leaves was not measured and N content was used as an alternative measure. Unfortunately these data were either very variable or inconclusive. Only the additional N present at harvest in the N0, GAI 5 or Ncf crops that had received N as foliar urea indicated that N had been taken up from these applications.

The percentage of N recovered by the crops from the late-N applications of foliar urea was very variable, ranging from less than 10 % at Sutton Bonington, and between 40 and 70 % (in some cases in excess of 100 %) at IACR-Rothamsted. There were no significant differences in the amounts recovered from the different foliar urea treatments either in total or in the grain alone, despite this wide variability in percentage recovery. The only exception was the N0 crop which recovered a significantly smaller amount of N in the grain than the other crops at IACR-Rothamsted in 1995. This made comparisons between recoveries recorded in other studies very difficult. As discussed in section 4.6, the percentage recoveries were, in some cases greater than 100 % of the N applied as late-N. This suggests that additional N must have been taken up by the crop, probably from the soil. Therefore it was not possible to determine exactly how much N from the foliar urea applications had been taken up before harvest or where the majority of it was partitioned within the plant. The difference between the percentage recovery of foliar urea in the grain and in total by the whole plant, suggested that by harvest most of this additional N had been partitioned to the grain. This may have occurred immediately after application of foliar urea. The results of the N^{15} labelled urea experiment, showed that within the first 96 hours after application of foliar urea to the flag leaf only, at anthesis, the majority of the N^{15} was present in the rest of the plant rather than remaining in the flag leaf. Below *et al.*, (1985)

showed that N from foliar urea applications to maize at anthesis was quickly transported to the ear and not stored in the stem.

Poulton *et al.*, (1990) found that from applications of 40 kg N ha^{-1} of N^{15} labelled foliar urea to winter wheat, at either flag leaf emergence or ear emergence, a total of 63 % was recovered at harvest and of this 45 % of the N^{15} was present in the grain, 9 % in the straw and 9 % in the soil. Other experiments using N^{15} labelled foliar urea, Powlson *et al.*, (1987) and (1989), showed that 62 and 70 % respectively of the N^{15} applied at anthesis was recovered in total at harvest, of which approximately 9 % was present in the straw and 89 and 91 % respectively in the grain. They found that a greater proportion was recovered from foliar N applications than from soil N fertilizer applied at the same time. These reports support the data presented in this study. Of the N present at harvest, the majority was contained within the grain with only an additional 10 % (of the late-N applied as foliar urea) present in the whole plant.

The inability to determine the exact proportion of foliar N recovered by the crop also makes it difficult to determine the proportion of the N that was measured as "lost" from the surface of the leaf over 96 hours, that was then subsequently taken up by the plant. The data for the total N content of the plant 96 hours after the application of foliar urea were too variable to be used to determine this, but as discussed in section 6.6.3, the majority of this exponential loss was probably uptake by the plant. Palta, Fillery, Mathews and Turner, (1991) used N^{15} labelled foliar urea to show that initial uptake by the plant in the first nine hours was rapid and that the rate of uptake followed the transpiration rate, so that a decline in the transpiration rate resulted in a decrease in N uptake. Interestingly, uptake by the main stem leaves was more rapid and more N was taken up in total than by the tillers, something that was not examined in this study, although care was taken to only sample main stems. This may be important in crops that have a large number of tillers as it may indicate a reduction in the potential for N uptake by the whole plant.

Although it was not possible from any of the data collected to determine the amount of urea lost by volatilization from the leaf surface or by evaporation from the spray droplets in flight, these factors should not be discounted. There are not usually a large number of urease enzymes present on the leaf surface and Bowman and Paul (1990 b) found that there was little hydrolysation of urea on the shoots of bluegrass turf and volatile loss was recorded as 5.3 % over 48 hours. If this figure was applied to the applications made in this study, then a minimum of 1.6 kg N ha^{-1} would be lost from the surface of the leaf in the same period after the application of 30 kg N ha^{-1}. However, Bowman *et al.*, (1987) recorded a 35 % loss of N by volatilization over a 24 hour period which would amount to 10.5 kg N ha^{-1}, from 30 kg N ha^{-1} applied in these experiments. Despite the inability to determine the actual recovery from the foliar urea applications, it is probable that in these experiments at least, and under the prevailing weather conditions at the time of application, there were not significant losses of N by volatilization, especially considering the large responses in yield and in total N uptake, when measured at harvest, by the GAI 5 crops that received late-N applications as foliar urea. The data collected from the N^{15} labelled urea experiment do indicate that some of the applied N was probably lost by volatilization. There was approximately a 10 % difference in the amount of N^{15} present on the leaf surface initially and that present in the whole plant 96 hours later, under the experimental conditions described. Losses in the field may have been more or less dependent upon the weather conditions at the time of application although, as there were no extremes of temperature or excessive rainfall, it is unlikely that this would have had a major effect on the amount lost by volatilization or washed off to the soil surface.

Despite the variability of some of the data, it may be possible to calculate the approximate fate of the late-N applied as foliar urea to Canopy Managed (GAI 5) crops. The calculations were based upon data obtained from the application of 30 kg N ha^{-1} as foliar urea at ear emergence or anthesis, without the addition of adjuvants at IACR-Rothamsted in 1995. Of the total spray applied, approximately 60 % was intercepted by the crop. The remaining 40 % could be accounted for by spray drift 2 - 5 %, (T. Robinson, personal communication); loss by volatilization: 10 % (from the N^{15} experiment, section 7.3); with

the remainder deposited onto the soil surface, 25 %. Of the N deposited onto the crop, approximately 90 % was 'lost' from the crop surface over 96 hours (the amount measured as intercepted minus the amount remaining at 96 hours, table 6.6), with 10 % remaining on the crop. The change in N content of the crop over 96 hours (table 6.7), shows that of the amount 'lost' from the crop, 35 % had been taken up over that period. This figure was similar to that measured over 12 hours by Bowman and Paul (1990 a). If 10 % is assumed to have been lost by volatilization during the 96 hours, 55 % of the amount 'lost' still remains unaccounted for. However, the amount of N present in the crop at harvest and the calculated percentage N recoveries (tables 4.6, 4.7 and 4.8), suggest that the majority of the 55 % remaining was taken up. Of the total N applied, (basal N plus late-N), 64 % was recovered at harvest, of which 87 % was present in the grain. Although the recovery of late-N was in excess of 100 % of the 30 kg N ha^{-1} applied, 123 % in total with 112 % present in the grain, the difference in the two figures was similar to that of the recovery of the total N applied. Therefore it is probable that of the N taken up, 90 % was present in the grain at harvest.

It is probable that each of the factors examined in sections 7.5 and 7.6 would have had some effect upon the rate of uptake of urea. However, to some extent any effects of these factors, which were the side of the leaf to which foliar urea was applied, the amount of N applied, the growth stage of the plant, the age of the leaf and whether adjuvants were used, were obscured by the large variability in the data produced. These inaccuracies were probably due to an unreliable experimental procedure, that initially appeared to be reasonably suitable for use under controlled environment conditions. The precision of the experiments may have been improved by greater replication and reduced handling of the plant material. However, it is possible to draw some conclusions from the data produced, but first the differences between the field and controlled environment experiments must be considered.

One difference was the use of the winter wheat variety Cadenza and not Mercia for the experimental plant material. Cadenza was chosen solely because it has a very low

vernalization requirement (National Institute of Agricultural Botany 1996), making it easy to grow in glasshouses. This may have altered the "loss" of N from the leaf surface and also the assumed uptake, when compared to Mercia, by simply having a different cuticle structure, due to the different varieties and the different conditions under which they were grown. Secondly, single plants were grown in an artificial medium of perlite and Terra-green receiving sufficient nutrients to grow and develop normally but without the risk of large amounts of N being available to the plant which could mask any effects of the foliar urea treatments, as was possibly a factor at Sutton Bonington in 1995. Although exact measurements of the N content of the plants were not taken, it is likely that it was lower than the plants grown in the field as a smaller amount of N was available to them than plants grown in the field. Plants containing smaller amounts of N in the leaf, may take up N more rapidly as the concentration gradient across the cuticle may be larger than that of plants containing larger amounts of N and be different enough to facilitate a more rapid uptake. Plants containing a larger amount of N would not have such a pronounced concentration gradient with the result that uptake would be slower. The plants were also not subject to the stresses related to water-logging or drought but were probably under greater disease pressure, particularly from *Erysiphe graminis*, than would be the case under field conditions due to the warmer and more humid conditions. Thirdly, there is evidence (S.R. Moss, personal communication) that the cuticle of leaves of plants grown in glasshouse conditions is thinner and provides less of a barrier to uptake than the cuticle of leaves from field grown plants. Uptake may therefore be more rapid. Lastly uptake may also be affected in other ways. For example, uptake may be increased by warmer, more humid conditions or by a change in the transpiration rate. Temperatures that are too high may have the opposite effect in reducing uptake if stomata become closed, assuming that Palta *et al.*, (1991) were correct in relating the uptake of foliar urea to the transpiration rate.

When examined on both the flag leaf and flag -2, the age of the leaf when foliar urea was applied did not appear to affect the rate of uptake of urea. Several authors have shown that urea uptake was greater by younger leaves (Cain, 1956; Robertson and Kirkwood, 1969;

and Klein and Weinbaum 1985), something that could not be confirmed by the data collected in this study. There are no reasons to suggest that this would not be the case for these foliar urea applications. Powlson *et al.*, (1987 and 1989) showed that a greater amount of foliar urea was recovered at harvest from applications made at anthesis, compared with those made earlier or later in the season. The percentage recoveries of foliar urea from field applications were also somewhat variable, but there were no indications that applications made at one specific crop growth stage had resulted in a greater amount of N being recovered. If these data examining $t_{0.5}$ for increasing leaf age are also used as growth stage indicators, they suggest that uptake was not affected by crop growth stage.

Several authors have shown that uptake of urea was more rapid over the abaxial (lower) leaf surface, for example Cain (1956) and Franke (1967). There are no reasons to expect that this was not the case in this study, but the results from controlled environment experiments did not show any differences. These measurements were made on leaves that had received similar, if not identical amounts of urea on each surface of the leaf, whereas in a field situation the only deposition onto the abaxial surface would be from spray droplets deposited there by turbulent air movement within the crop canopy. So it is not clear how important more rapid uptake over the abaxial surface would be in determining the final amount of N that would be recovered by the crop. This might become a more important consideration if electrostatic or air-assisted sprayers were used to apply foliar urea as opposed to the more conventional hydraulic sprayers used in this study. Both the electrostatic and air-assisted sprayers result in greater penetration to lower leaf layers within the canopy and increased coverage of the plant material.

There are no studies examining the effect of the amount of N applied or the use of adjuvants on the uptake of N from foliar urea applications but the addition of adjuvants appeared to improve the rate of uptake measured using $t_{0.5}$ from foliar urea applications, something that could be reasonably expected.

8.1.2 The use of foliar N for the prolongation of GAI

One of the many purposes of the different foliar urea treatments applied at both IACR-Rothamsted and Sutton Bonington was to maintain the duration of GAI and thereby delay the rate of senescence of the canopy, leading to continued photosynthesis and dry matter accumulation. Each of the foliar urea applications resulted in a prolongation of GAI, irrespective of the method of application, timing, amount of N applied, or whether adjuvants were used, compared to a GAI 5 crop that did not receive late-N. Unfortunately in both years and at both sites the canopy died very rapidly in the last two weeks of July with the very warm, sunny weather so that it was not possible to differentiate between the effectiveness of the treatments in altering the date of complete extinction of canopy green area. It is important to note however, that although the Canopy Managed (GAI 5) crops had similar GAIs to the conventionally fertilized ones, they did not retain their green area for as long and the green area became fully extinct somewhat earlier, in spite of the application of late-N. At IACR-Rothamsted in both 1994 and 1995, the N content at harvest of the GAI 5 crops that did not receive late-N was significantly lower than that of the conventionally fertilized crops.

After anthesis the wheat plant is unable to form new green tissue, so it is the N content at this point that could be most important in determining the pattern of canopy senescence. N applied after anthesis therefore may only be of benefit to the grain protein and might not alter the longevity of green area. The N^{15} experiment described in chapter 7 suggests that foliar urea applications made at anthesis were probably mostly transported directly to the ear from the flag leaf but it is not clear whether N from foliar urea applied at flag leaf emergence or just prior to ear emergence would have had a similar fate. It is probable that it would have been more involved in leaf metabolism, having an effect of delaying senescence by increasing the amount of N within the leaf and the whole plant, such that more N would be available for remobilization to the grain after anthesis. However, an additional amount could also remain in the leaf maintaining green area duration.

Consequently, crops with a greater N content at anthesis may not senesce as rapidly as crops with lower N contents. This could be illustrated by comparing the contrasting N contents of the N0, GAI 5 and Ncf crops before each received late-N at anthesis at IACR-Rothamsted in 1995, table 6.7. These crops contained 44.9, 154.2 and 200.5 kg N ha^{-1} respectively before extra late-N as foliar urea was applied. The pattern of senescence described in figure 4.2, indicates that the duration of the green area of the Ncf crop was longer than that of the GAI 5 and N0 crops. The green area of the N0 crop became extinct before that of the GAI 5 crop and Ncf crops retained some green area after the GAI 5 crops senesced, although there was only a few days difference in this point between the three basal crops. This suggests that it was the N content at anthesis, determined by the amount of basal N applied, that was the most important factor in determining GAI duration. Unfortunately, no measurements were taken of the N content at anthesis of other GAI 5 crops that had received late-N as foliar urea at flag leaf emergence or prior to ear emergence. Other factors which are important in determining the rapidity of senescence are the combination water availability and the weather conditions. Warm, sunny weather and dry soil conditions will promote senescence whereas crops in wet, cool and dull conditions may not senesce as rapidly, thus maintaining green area for longer. However it is important to note that the foliar urea applications did alter the pattern of senescence of the GAI 5 canopies such that senescence was delayed and occurred more slowly. The delay in senescence was similar between all the late-N treatments applied to the Canopy Managed crops and was probably related to the N content of the GAI 5 crops, those receiving late-N at any point in the season almost certainly contained more N at anthesis than the GAI 5 crop which did not receive late-N, which therefore senesced more rapidly.

8.1.3 **The effect of foliar N on grain yield and quality**

As has been discussed in section 3.6, the yields of grain obtained from the experiment at IACR-Rothamsted in 1994 were considerably lower than might be expected from the variety Mercia and the site and this was largely due to the presence of a large number of weeds. However, irrespective of this problem, a difference in yield between the basal N

treatments could be observed and as the data for the other two field experiments show, the Ncf crop yielded the largest amount of grain, but not a significantly greater amount than the GAI 5 crops that received applications of late N. It is this lack of distinction which is therefore important, that under the regime of Canopy Management, where additional late-N was applied, the grain yields obtained did not differ significantly from those produced from more conventional fertilization methods.

As biomass partitioning to the grain was seemingly unaffected by the application of late-N and the only significant difference in HI between the Ncf crop and the GAI 5 crop that did not receive late N was recorded at IACR-Rothamsted in 1995, then it is likely that Canopy Management did not affect the formation of grain yield. Similarly the partitioning of N to the grain was unaffected by the application of late-N and again there were no significant differences between the Ncf and GAI 5 crops. This suggests that despite the reduction in the amount of N available to the crop in the spring under Canopy Management, this does not have a detrimental effect on yield or quality of the grain. Grain quality attributes such as specific grain weight (hectolitre weight), thousand grain weight and Hagberg falling number were also unaffected by either the amount of basal N applied or the application of late-N either as foliar urea or soil-applied N.

Only at Sutton Bonington in 1995 were the yield responses to late-N application as foliar urea more variable, mainly due to the large amount of soil mineral N present in the spring which probably masked any effects of the late-N treatments. These did not show any significant effects over the basal N treatments alone. Therefore Canopy Management did not have a detrimental effect upon grain yield or quality compared to the Ncf crop and under the regime of Canopy Management, the highest yields and best quality grain (in terms of the highest protein content) were obtained from GAI 5 crops that had received late-N applications, irrespective of the amount, timing, source of N or whether adjuvants were used.

8.1.4 The production of bread making quality wheat

The protein content of grain must exceed a threshold of 11 % for it to be suitable for bread making and attract a premium at sale, something that has become of much greater importance in recent months with the continuing reduction in grain prices. As a result, this premium must be guaranteed as much as is possible within the constraints of the variation inherent within a natural biological system.

The data presented in this study have indicated that Canopy Managed crops do not tend to reach the required grain protein content, even with applications of late-N. There were no significant differences in grain yield between the GAI 5 crops that received late-N and the Ncf crops at IACR-Rothamsted.. At Sutton Bonington the combine yields showed that there were no significant differences between any of the GAI 5 crops (including the GAI 5 crop that did not receive late-N) and the Ncf crop. However at both sites it was only the Ncf crops that exceeded 11 % protein. Although late-N applied as foliar urea to GAI 5 crops did show a significant improvement in grain protein content at Sutton Bonington and at IACR-Rothamsted in 1994 and 1995, it was probably the basal N applications that had the greatest effect on grain protein content, as all the Ncf crops, which received more N in total than the GAI 5 crops, exceeded 11 % grain protein.

Crops must therefore have sufficient N available for grain filling to meet bread making requirements. Insufficient N will result in poorer quality grain and a corresponding reduction in the financial return given by the crop. The additional N taken up from late applications of foliar urea, which avoid the problems of potentially poor uptake from soil applications in the summer, may be sufficient to ensure that this quality threshold was reached. This may be especially important for Canopy Managed crops which may not have enough N available from soil mineral N and basal N fertilizer applications to reach the desired protein content. However, it is important to note that foliar urea may not always be successful in raising the grain protein content to the desired level.

8.1.5 The most effective method for the application of foliar N

An examination of the uptake and utilization of late-N by Canopy Managed crops when different treatments were applied should allow the most efficient method of applying late-N to be determined. It has been demonstrated that under some circumstances, late-N as foliar urea can be of benefit, not only to GAI 5 crops but also to N0 and Ncf crops. However, it is possible that this would not always be the case, as illustrated by the experiment carried out at Sutton Bonington in 1995 which did not show positive effects from the applications. This was perhaps mainly caused by the large amounts of residual soil mineral N present in February which masked any treatment differences caused by the application of late-N as foliar urea and did not allow differentiation between the N0, GAI 3 and GAI 5 basal N treatments. There is some evidence of the more variable effects of foliar urea application on grain protein content and this suggests that late-N cannot always be relied upon to ensure that bread making quality is reached.

Soil applied N can only be taken up under moist soil conditions, which cannot be guaranteed especially around the time of anthesis. It has been suggested by the N^{15} experiment described in this study, that N from foliar urea applied at anthesis was transported directly to the ear, but it is unlikely that this would be the fate of N sourced from the soil when taken up at a similar time, but there are no published data to support this. It is reasonable to assume that N taken up by the roots would be involved in normal plant metabolism even when sourced from "late" soil applications, as no differentiation could be made by the plant on the source of N available to it in the soil. The evidence from IACR-Rothamsted in 1994, suggested that late-N applied either as foliar urea or as soil applied calcium nitrate to a GAI 5 crop at ear emergence had similar effects on GAI prolongation, grain yield and quality and N uptake.

Late-N applied as foliar urea showed a reasonably consistent benefit in prolonging the duration of GAI of Canopy Managed crops at IACR-Rothamsted. The effects of late-N on grain yield, grain quality, N uptake and N recovery are more variable; for instance, greater

than 100 % of the applied foliar urea was recovered in some instances at IACR-Rothamsted in 1995. However, as there was little difference in the agronomic effects of the late-N treatments, it is perhaps the requirement to ensure that the N content at anthesis is as high as possible in order to alter the pattern of senescence of the canopy (section 8.1.1), that is the most important factor in determining the application if late-N to be made. On this basis applications of foliar urea before anthesis, at flag leaf or ear emergence may supply sufficient additional N to prolong the duration of canopy green area.

It is important to note that the application of 60 kg N ha^{-1} did not result in an increase in yield, grain quality and percentage N recovery that was commensurate with the additional amount of N applied compared to when 30 kg N ha^{-1} was applied and this additional N was therefore used less efficiently. Although adjuvants did not have a detrimental effect upon N uptake or other agronomic factors such as yield when measured under field conditions, there were significant effects on the amount of N present on the leaf surface over time when measured under controlled environment conditions. If the N lost from the leaf surface, for the purposes of this discussion only, were assumed to be entirely due to uptake, then the addition of Silwet L-77 and LI-700 significantly improved $t_{0.5}$ and consequently N uptake compared to when no adjuvant was added. These differences have been difficult to resolve (8.1.1), but this may suggest that the field experiments were too coarse a system in which to observe the rapid action of the adjuvants and that the adjuvants were not suitable for use with the application of a nutrient, being designed to improve the uptake of pesticides which tend to be polar molecules whereas urea is not charged.

Therefore it appears that applications of 30 kg N ha^{-1} as foliar urea made either at flag leaf or ear emergence have the potential to increase the total N content of the plant by an amount sufficient to extend the duration of canopy GAI, increase yield and improve grain quality, most particularly under low soil mineral N conditions. If the results from the controlled environment experiments show the true effect of adjuvants then a penetrant such as LI-700 or a spreader, for example Silwet L-77, may improve the rate of N uptake by reducing $t_{0.5}$.

8.2 CONCLUSIONS

This study has examined the uptake and utilization of foliar N by Canopy Managed crops and although the results obtained are not conclusive, they indicate that foliar urea is an efficient method of applying N later in the season to Canopy Managed crops, avoiding the problems of little or no uptake from soil applications in dry conditions or leaching losses when very wet. N sourced from foliar urea can also confer some benefit on conventionally fertilized and N0 crops resulting in some occasions in an increase in grain yield and N uptake. Thus the hypothesis outlined in section 1.5 has been proved.

8.2.1 **Uptake and utilization of foliar N**

The hypothesis that foliar urea is an efficient method of applying foliar urea to Canopy Managed winter wheat crops is supported by the evidence presented in this study. On all occasions the green area of GAI 5 crops was prolonged by the application of late N as foliar urea, but only in some cases did it result in an increase in grain yield or quality. The additional N delayed the senescence of the crop canopy probably by reducing the rate of remobilization of N from the leaves and stems. This resulted in continued photosynthesis, allowing greater dry matter accumulation than in crops that had not received foliar urea, yields of grain were consequently increased and their quality (*i.e.* protein content) improved by the larger amount of N available to the crop. A maximum of 60 % of the applied N was measured as being intercepted by the GAI 5 crops, with the top half of the canopy being the most important part of the crop for both deposition and probably uptake of N. The amount of N deposited and the pattern of deposition were affected by the orientation of the leaves in the canopy and whether the ear was present. Foliar urea applied prior to ear emergence penetrated more deeply into the canopy, whilst applications after full ear emergence had reduced penetration to the lower leaves, as the ear was also important for N interception.

Of the N deposited, a large proportion must have been taken up by the crop to produce the yield and quality increases that were measured and this was illustrated by the significantly

greater N contents of the GAI 5 crops that received foliar urea, at IACR-Rothamsted at harvest. The amount of N recovered from the foliar urea applications was variable, and no conclusions can be made on the exact amount recovered by the crops. From the evidence presented in the N^{15} experiment it is likely that foliar urea applied at anthesis may be transported directly to the ear, but applications made earlier in the development of the plant were probably used to supplement the existing N already present in the leaf.

N uptake from the leaf surface probably followed an exponential pattern and in this study was not shown to be significantly affected by the side of the leaf to which urea had been applied, the age of the leaf or growth stage of the plant or the amount of N applied. Only the addition of the adjuvants Silwet L-77 (a spreader) and LI-700 (a penetrant) increased uptake rates.

8.2.2 Suggestions for further work

It will be important to measure accurately the N lost from the application of foliar urea either by spray drift, volatilization and deposition onto the soil. This will greatly help in the estimation of the percentage recovery of foliar urea by the crop, whatever its N status or the method used to determine the amount of basal N fertilizer applied in the spring. Further investigations of the fate of N within the crop using N^{15} would also be of great benefit and this would also help to estimate volatilization losses.

The level of precision in some of the experiments, especially in controlled conditions was not satisfactory. Greater accuracy may be achieved by increased replication in both field and controlled environment experiments, and larger numbers of plants or plant parts should be sampled for each set of measurements.

The effectiveness of foliar urea applications may be improved by the use of alternative spray technology such as air-assisted or electrostatic sprayers, the use of different types of nozzle other than conventional hydraulic ones, the use of lower water rates, or the addition of an

adjuvant that would promote uptake. The adjuvants tested in this study tend to promote the uptake of charged compounds and urea is not charged. Therefore, the use of electrostatic sprayers in conjunction with a suitable adjuvant may improve uptake significantly. Changing the spray technology used to apply foliar urea may be the only immediate way of improving the amount of N that is deposited on to the crop and so is available for uptake.

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APPENDIX: CROP HUSBANDRY

A.1 IACR-Rothamsted 1994

OPERATION	DATE
ploughed	10 September 1993
spring tined (twice)	23 September 1993
rotary harrowed	24 September 1993
methiocarb 220 g ha^{-1} (Draza 5.5 kg ha^{-1})	21 December 1993
metsulfuron-methyl 6 g ha^{-1} (Ally 30 g)	24 May 1994
fenoxaprop-P-ethyl 87.5 g ha^{-1} (Cheetah Super 1.5 l)	24 May 1994
fluroxypyr 150 g ha^{-1} (Starane 2 0.75 l)	24 May 1994
chlorothalonil & flutriafol 750 & 94 g ha^{-1} (Halo 2.0 l)	13 June 1994
fenpropidin 375 g ha^{-1} (Mallard 750 EC 0.5 l)	13 June 1994
triazophos 353 g ha^{-1} (Hostathion 840ml)	17 June 1994
grain combined	16 August 1994

All pesticides were applied in 200 l ha^{-1} of water unless stated otherwise.

OPERATION	DATE
ploughed & furrow pressed	02 September 1994
methiocarb 220 g ha^{-1} (Draza 5.5 kg ha^{-1})	13 October 1994
isoproturon 250 g ha^{-1} (Hytane 500 SC 2.5 l)	08 November 1994
pendimethalin 1320 g ha^{-1} (Stomp 400 SC 3.3 l)	08 November 1994
cypermethrin 25 g ha^{-1} (Ripcord 250ml)	11 November 1994
fenoxaprop-ethyl 120 g ha^{-1} (Cheetah R 2.0 l)	20 April 1995
2-chloroethylphosphonic acid & mepiquat chloride	01 May 1995
232.5 & 457.5 g ha^{-1} (Terpal 1.5 l in 300 l & Vassgro	
Wetter 0.3 l)	
chlorothalonil & flutriafol 750 & 94 g ha^{-1} (Halo 2.0 l)	05 May 1995
tridemorph 262.5 g ha^{-1} (Calixin 0.35 l)	05 May 1995
tebuconazole & triadimenol 250 & 125 g ha^{-1}	20 June 1995
(Silvacur 1.0 l)	
grain combined	11 August 1995

All pesticides were applied in 200 l ha^{-1} of water unless stated otherwise.

A.3 Sutton Bonington 1995

OPERATION	DATE
ploughed & pressed; power harrowed	02 October 1994
diflufenican 100 g ha^{-1} & isoproturon 1000 g ha^{-1} (Panther 2 l)	11 March 1995
mecoprop-P 1380 g ha^{-1} (Duplosan 2.3 l)	11 March 1995
chlormequat 1610 g ha^{-1} (Chlormequat 70 2.3 l)	09 April 1995
prochloraz 405 g ha^{-1} (Sportak 45 0.9 l)	09 April 1995
fenpropidin 750 g ha^{-1} (Patrol 1.0 l)	09 April 1995
fluroxypyr 200 g ha^{-1} (Starane 2 1.0 l)	21 April 1995
2-chloroethylphosphonic acid & mepiquat chloride 201.5 & 396.5 g ha^{-1} (Terpal 1.3 l in 300 l)	03 May 1995
tebuconazole 250 g ha^{-1} (Tebucon 1.0 l)	15 June 1995
pirimicarb 280 g ha^{-1} (Aphox 50 % w/w)	30 June 1995
grain combined	10 August 1995

All pesticides were applied in 200 l ha^{-1} of water unless stated otherwise.