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AN INTEGRATED APPROACH TO NITROGEN NUTRITION FOR WHEAT

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'AN INTEGRATED APPROACH TO NITROGEN NUTRITION FOR WHEAT'

by

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Objectives

The objective of this work was to analyse and assess the concept of 'Canopy Management' with N. The term 'Canopy Management' was adopted, through this Project, to describe a rationale for wheat husbandry whereby inputs such as nitrogen are optimised according to their effects on the size of the crop's green canopy, and hence on it's photosynthetic capacity. 'Canopy Management' was seen as an alternative to the more conventional approach whereby husbandry inputs, particularly nitrogen, are adjusted in proportion to 'expected yield'.

The hypothesis under test was that the 'effectiveness of limited amounts of N can be enhanced, and yields maintained, if applications are timed for when field conditions favour N uptake, and uptake coincides with when canopy expansion is necessary'. It was intended that the outcome of this research should be a 'grower's guide', identifying conditions which would maximise uptake from each nitrogen dressing and minimise the need for other agrochemicals, particularly fungicides.

Introduction

Farmers are currently pressed to reduce their use of fertiliser N. This project was targeted towards gaining most benefit from the fertiliser N used. Current recommendations for the amount of N providing for optimum economic performance of winter wheat have been derived from extensive field experimentation (Anon, 1994). Comparison of predicted N optima with optima measured by experiment show little difference on average, but in individual cases the two can be markedly adrift (Sylvester-Bradley & Chambers 1992); predictions of N optima can be more than 100kg/ha N different from those measured. Current recommendation systems for N appear to be satisfactory for dealing with the 'average' crop in 'average' growing conditions, but they fall short of providing the precision that growers require in order to apply them with confidence to an individual crop. Given the extensive nature of the empirical evidence it would seem unlikely that confidence will be improved simply through further extensive tests. Rather, it appears necessary to provide the Industry with ***principles*** whereby they can judge the N requirements for their own particular circumstances.

Currently, predicted optima include adjustments to 'allow' for (a) the anticipated supply of N from soil and (b) the anticipated demand by the crop. The estimate of crop demand is ‘expected yield’ and adjustments are based on some experimental evidence as well as apparent ‘self-evidence’ that grain yields and amounts of applied N must be positively associated.

Experiments on winter wheat and most other crops show that response to N is initially large but with increasing amounts, the additional yield produced becomes gradually smaller until no further yield is produced (Figure 1).

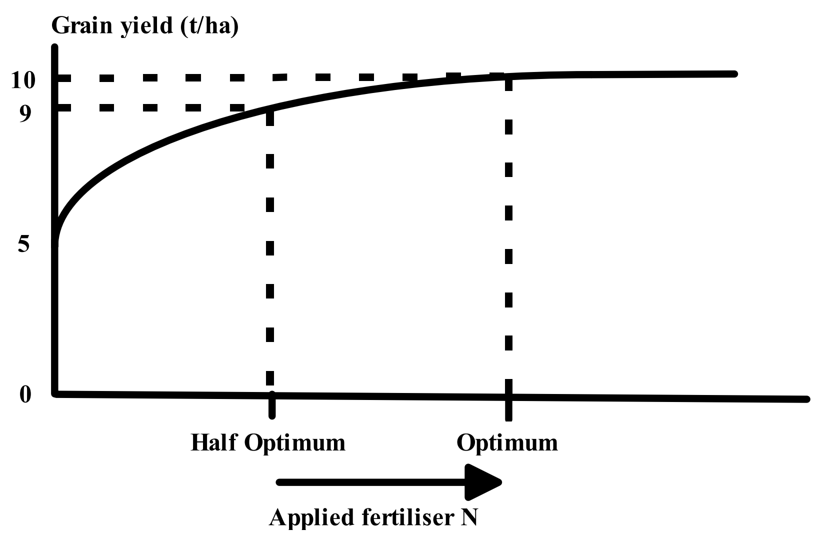


Figure 1. The effect of increasing fertiliser N on the grain yield of winter wheat.

The form (i.e. the shape) of this response is generally quite stable (George, 1984): however, the asymptote and particularly the intercept show considerable variation (Sylvester-Bradley *et al.,* 1995). The intercept is largely governed by the supply of N from the soil, whilst the asymptote is set by the growing conditions of the site and season. Often, soil N is sufficient for production of about half of the potential yield. Thus the form of the response with added fertiliser is such that the first half of the normal N requirement provides about 90% of the potential yield; the second half appears to be used less efficiently, providing for less than 10% of the potential yield.

Nevertheless, it is important that growers exploit the full response to N because the return from the final 10% of the yield may, for many crops, be responsible for generating most of their profit.

The familiar diminishing response of wheat yield to fertiliser N may encourage some growers to use more fertiliser N than is necessary. The form of the response appears to indicate that any shortfall in N provision (i.e. on the steep part of the response curve) will seriously compromise yields and risk a financial penalty. On the other hand, yields of crops which are over fertilised will be near maximal (now that the exacerbating effects of excess N on lodging and disease can be more reliably counteracted) and the only penalty will be the cost of surplus fertiliser. Over-fertilised crops will also be less evident to the grower, as they will appear satisfactorily green and dense. Therefore any unnecessary expenditure on fertiliser N and the increased loss of nitrate to groundwater from excessive N applications will be less obvious than any shortfalls. This will tend to encourage advisors and growers to err on the side of caution and be reluctant to reduce N rates, without good reason that it is ‘safe’ to do so.

The small yield changes associated with near-optimal amounts of N indicate that there are major inefficiencies amongst the processes which lead from N application to grain formation. Hitherto, the Industry appears to have accepted that the complexity of the intervening steps is such that a search for the inefficiencies would prove fruitless. In particular, the in-crop processes have eluded useful summary; it has always been clear that nitrogen makes wheat crops greener, more lush and thicker, producing more ears which are heavier, but most of these effects have appeared subjective and highly variable.

However, in 1990, we proposed a quantitative link between fertiliser N, crop growth and yield formation (Sylvester-Bradley *et al*., 1990). An examination of data from crops of Avalon grown in the early 1980's (Willington *et al*., 1982; 1983) provided evidence that, although there was no clear proportionality between the amount of fertiliser N applied and the expansion of the crop's canopy, there was an association with the total amount of N taken up (from both soil and fertiliser). This relationship was surprisingly direct, indicating that each hectare of the wheat crop's green surface was associated with 30 kg of N in those same tissues. The observation had the merit of linking the two, previously rather separate, approaches of soil scientists and crop scientists to the problems of N fertilisation, and it provided a quantitative framework against which to investigate the role of N in yield formation. This framework is illustrated in Figure 2 as a ‘step-diagram. The initial independent variable is fertiliser N (bottom, right), and the dependent variable in each relationship, or step, becomes the independent variable of the subsequent step; the second step is the proposed link between relationships accepted in soil science and accepted in crop science, and which provides the basis for Canopy Management.

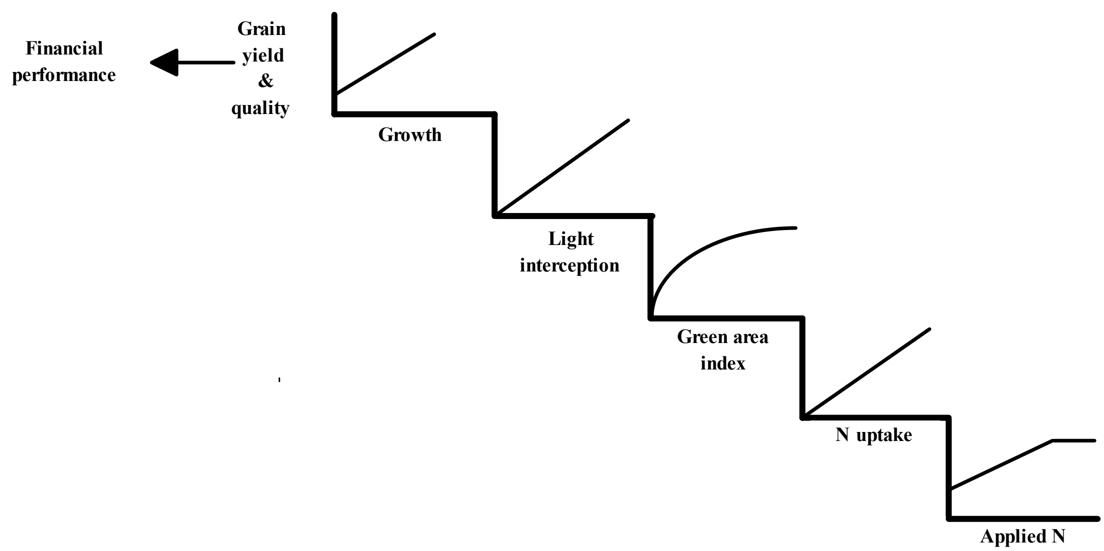


Figure 2. Schematic ‘step-diagram’ of the theoretical framework relating N application to yield formation. (Static model for the grain filling period).

The complete scheme in Figure 2 provides a simple yet quantitative summary of the processes which become affected from the application of fertiliser N through to the formation of grain yield. Starting with the first step (at the bottom of the diagram), each step can be described as follows :

N uptake

The amount of N taken up by the crop is determined by soil supply (N uptake without N applied) plus a relatively constant proportion of the fertiliser N applied, up to a point where no further N is taken up. Previous evidence (Vaidynathan *et al.*, 1987) suggests that an amount equivalent to 100% of the mineral N in the top 90cm of soil in February is recovered by the unfertilised crop.

On average, the proportion of fertiliser N recovered by the crop is about 60% (Bloom *et al.*, 1988). This proportion also applies to the amounts which just exceed the optimum amount required for grain yield; a feature which is exploited for the production of extra grain protein in crops grown for breadmaking.

Canopy Expansion

The amount of N taken up by the crop directly relates to the size of the crop's green surface (Sylvester-Bradley *et al*., 1990). Each hectare of green surface requires 30 kg of N to be taken up. Similar relationships have been reported in the ecological literature but they have not been widely validated with arable or horticultural species and conditions (Grindlay, unpublished). Canopy expansion in wheat is completed with the emergence of the flag leaf and ear. Thus the first two steps in Figure 2 apply to the period between the main application of fertiliser (normally in April) and ear emergence (normally at the end of May).

Light interception

It is widely accepted that the proportion of sunlight intercepted can be related to the size of the crop's green canopy by analogy with Beer's Law which states that the attenuation of light by a fluid increases exponentially with density. Thus, as crop canopies become larger, each successive increment in size captures a successively smaller amount of additional sunlight (Monsi & Saeki, 1953).

Biomass production

In the majority of temperate growing systems, crop yield is controlled by the amount of solar energy intercepted by the crop's foliage. Usually about 1.5 grammes (g) dry matter are produced from each megajoule (MJ) of energy intercepted (Monteith, 1977). This ‘conversion efficiency’ ($\in$) is generally stable unless crops are droughted or are deficient in mineral nutrients (Gallagher & Biscoe, 1978).

Grain formation all takes place after anthesis, and crop growth after anthesis is almost all due to grain formation. Thus grain yield is primarily dependent on photosynthesis after anthesis; any inhibition of photosynthesis in this vital phase has a strong bearing on grain yield. Thus the third and fourth steps in Figure 2 apply primarily to this post-anthesis phase. However, there is also some redistribution to the grain of carbohydrates and proteins assimilated prior to anthesis (Evans & Wardlaw, 1996), so these two steps must be considered to describe a ‘yield forming period’ which begins a little before anthesis.

It is a consequence of this scheme that the relationship between growth before and after anthesis will be indirect, and hence that harvest index (the ratio of grain weight to total crop weight) will be variable. This conflicts with previous analyses which have maintained that harvest index is a conservative characteristic of wheat crops in the UK (Austin, 1982).

Nitrogen redistribution and grain quality

Nitrogen uptake primarily takes place before anthesis, whereas grain protein formation takes place after anthesis. Grain protein formation thus depends upon extensive redistribution of nitrogen from the leaves to the grain during anthesis. This, together with a small amount of N uptake from roots or soil after anthesis, results in about three quarters of the crop’s N being deposited in the grain at the time of harvest (Austin, 1982). This approach determines that grain N concentration (and therefore the concentration of grain protein that is so important for breadmaking) must be a consequence of the success of N uptake during April and May, and the success of the photosynthesis that supports grain formation.

However, there are important interactions between these two processes underlying the determination of grain protein: redistribution of N from leaves causes them to senesce, and so lose the photosynthetic function which is so important in supporting grain formation. Thus any effect on N redistribution will tend to have an exaggerated effect on grain N concentration. The step-diagram therefore highlights a need for care in managing N nutrition in a way that protein concentration of crops intended for breadmaking will not be compromised. This must be addressed in any protocol for Canopy Management.

Optimum canopy size

This step-diagram summarises a physiological framework for understanding N effects on yield formation in wheat, and provides an opportunity to rethink the way optimum amounts of fertiliser N are determined. Using this framework, the target for N fertiliser can now be described as: augmenting the supply of N from the soil to provide for a crop canopy sufficiently large to intercept as much of the incident sunlight as can be justified economically. If each component of Figure 2 is found to hold over the range of conditions in which winter wheat is grown, they may explain why most of the yield can be produced with only half of the optimum amount of fertiliser N; as increasing amounts of N are applied, proportionately more is taken up by the crop, and the canopy becomes proportionately larger, but the amount of extra sunlight intercepted diminishes. Thus it is the third step, derived from Beer's Law, which gives rise to the diminishing returns from increasing amounts of fertiliser. Instead of asking, "What is the optimum economic amount of fertiliser?", the crucial question now becomes, "What is the optimum size of canopy?"

The measure used to quantify canopy size is the ratio between the total surface area of its green components, the leaves, stems and ears, to the area of ground that it occupies. Thus a crop with 7 m^2 of green surface per m^2 of land has a ratio of 7. This ratio has been named the Green Area Index (GAI) and is dimensionless. Beer's Law invokes the concept of an 'extinction coefficient' (k) to relate the proportion of incident sunlight that a crop intercepts to the size of its canopy through the expression $1 - e^{-k.GAI}$. In effect, the 'extinction coefficient' describes the attitude of the intercepting surfaces (near vertical crop structures have small values for k whilst near horizontal crop structures have larger values). Thus crops mainly comprised of erect leaves need a large GAI to intercept all the sunlight whilst crops with more lax leaves can intercept all the sunlight with a smaller GAI.

The coefficients of the remaining steps in Figure 2 can be substituted in the Beer's Law expression to provide a complete *quantitative* scheme by which N may be considered to control yield. In mathematical terms the complete expression is as follows :

$$\text{growth in DM (g)} = S.\epsilon\ [(1 - e^{-k.CNR.(N_s+N_f.\ N_{rec})})] \ldots\ldots\ldots\ \text{(Equation 1)}$$

where the symbols are as defined in the following table :

Symbol	*Name*	*Units*	*Description*
S	total incident solar radiation	MJ	the amount of sunlight energy available during the yield forming period
ϵ	'conversion coefficient'	g/MJ	converts intercepted solar radiation to crop dry matter
k	'extinction coefficient'	-	relates the attenuation of light to the size of the canopy (measured as GAI)
CNR	'canopy N requirement'	kg/ha	the ratio between green area index (GAI) and the amount of N in the canopy
Ns	'soil N'	kg/ha	N recovered by the crop without any fertiliser N added
Nf	'fertiliser N'	kg/ha	the total amount of fertiliser N applied
N_{rec}	'N recovery'	ratio	the change in crop N content as a proportion of the N amount which caused it

This expression can be then differentiated to determine the point in terms of Green Area Index at which the additional benefit in grain yield exactly matches additional cost in terms of increased fertiliser used. Thus the optimum canopy size can be defined as follows :

$$\text{Optimum GAI} = \frac{\ln[(\varepsilon.k\ .S) / (c\ .DM)] - \ln[(CNR\ .v_N) / (N_{rec}\ .v_g)]}{k} \ \ldots\ \text{Equation. 2}$$

where c converts from g/m^2 to t/ha (=10^2), DM is the ratio of dry weight to fresh weight of the saleable yield, and v_N and v_g are the values of fertiliser N (£/kg) and yield (£/t) respectively and, k is taken as 0.6, an average figure from the literature (Hay and Walker, 1989). This expression now provides a basis for the definition of crop N requirement, with canopy size (GAI) being 'the diagnostic'. Hence the use of the phrase 'Canopy Management',

Substituting in Equation 2 the values estimated in preceding sections, and taking the yield forming period as 42 days at 18 MJ/m^2/day (756 MJ/ha), and v_N and v_g as £0.30/kg and £100/t respectively, optimum canopy size for winter wheat in the UK can be calculated as :

$$\text{Optimum GAI} = \frac{\ln[(0.60 \, x \, 756 \, x \, 1.5) / 10^2 \, x \, 0.85] - \ln[(30 \, x \, 0.30) / (0.6 \, x \, 100)]}{0.6}$$

$$= 5.2$$

Of course, some uncertainty attaches to this prediction; none of the coefficients is known with perfect certainty, and there may well be additional processes which have some bearing on the outcome. Nevertheless, this framework provides a rationale of acceptable authority and simplicity to be considered as a basis for fertiliser decision taking in commercial conditions. It seems worth avoiding further complexity unless this proves essential. Thus the tasks of the research described in this report are

(a) to test the premises on which the framework for Canopy Management is based, and

(b) to test for the advantages predicted from a Canopy Management approach compared to a more conventional approach to N fertilisation.

Predictions

The predicted optimum canopy size of 5.2 appears relatively small compared to canopy sizes of about 7 normally observed for commercial crops in the UK (Sylvester-Bradley & Scott 1990); it appears that Canopy Management might result in growing wheat with smaller canopies than is currently the case. Also, if CNR can be shown to be sufficiently stable, it appears that fertiliser N could be used to control expansion of the crop's canopy with sufficient precision for an optimum canopy to be created.

It appears that there could be two contrasting approaches to N nutrition for wheat. Firstly, conventional approaches may result in larger than necessary canopies in late May and early June but then these larger canopies remobilise much of the N stored in lower leaves and stems to provide for protein deposition in grain whilst the upper leaves provide a green, light intercepting canopy during later grain filling. The alternative Canopy Management approach uses N to limit canopy size to that necessary for efficient light interception in May and June but then requires N later in the season to prolong the canopy during grain filling when there is heavy demand on the crops foliage for N.

It seems theoretically possible that using fertiliser N in relation to canopy production should result in similar yields to conventionally fertilised crops, because a similar amount of sunlight energy should be intercepted and the efficiency with which light energy is converted into biomass should not be affected. Furthermore, more accurate allowances for soil N and the use of N later in the season should offer the potential to more closely match the supply of N to crop demand therefore reducing unpredictable variation in the optimum. The anticipated effect of these two approaches on canopy size is shown in Figure 3.

The Canopy Management approach to N nutrition for wheat not only offers the opportunity to save fertiliser, if for example soil supply is larger than expected, it also offers the industry a clearer justification to defend the use of fertiliser N. Furthermore, there may be additional benefits from the use of less fungicide, if disease progress is less rapid in the less lush canopies, and there may be reduced need for PGRs, if the less dense crops have thicker, stronger stems.

However, if this new approach to determining N applications leads to the production of canopies smaller than those currently produced, there may be smaller reserves of N at flowering and removal of N to meet the demands for protein deposition during early grain filling may cause earlier senescence of important light intercepting leaves during a period of high sunlight receipts. Thus the adoption of more moderate sized canopies may require applications of N later in the season to provide N for grain protein formation.

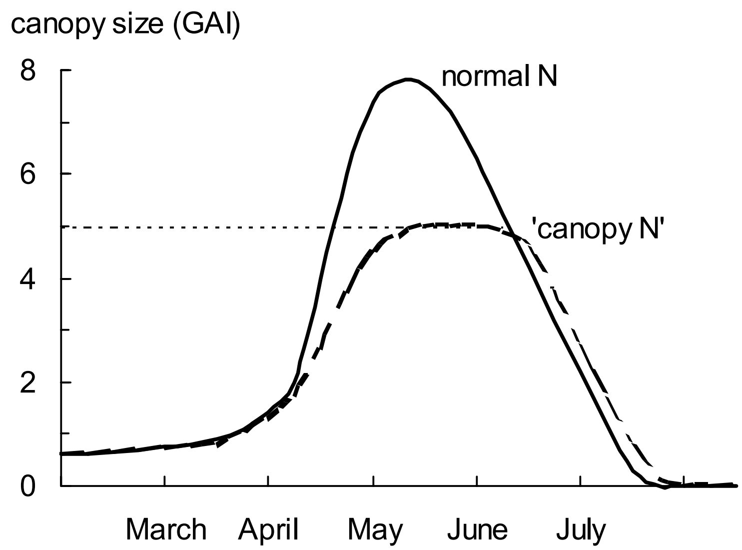


Figure 3. Schematic diagram for winter wheat comparing canopy development with normal N management with the intended course of canopy development with Canopy Management.

Supply of N for grain protein formation

Applications of granular N made late in the season especially when soils are dry, generally show poor recovery (Dampney, 1992). If the Canopy Management approach is to succeed, particularly for crops intended for breadmaking, reliable methods of supplying N to canopies during grain formation need to be identified. An approach commonly used in the production of wheat grain for breadmaking is to apply N as urea direct to the foliage during grain filling, thus eliminating transfer through the soil. Although only used to increase grain protein content, there does not appear to be any reason why foliar N cannot be applied to the foliage to replace N removed for grain filling from these smaller canopies, and thus to prolong canopy life. However, use of late foliar N has been shown to have its own inefficiencies (Powlson *et al.*, 1979) and therefore part of the research reported here examines work conducted at IACR Rothamsted to investigate how uptake of late applied foliar N might be improved in practice.

Rules for Canopy Management with N

Practical application of Canopy Management depended on devising a set of 'rules' by which N applications could be made to achieve the estimated optimum GAI of 5. These rules are as follows :

1. The optimum canopy size for photosynthesis is 5 GAI. To optimise light interception and maximise grain production, this canopy must achieved as soon as possible and be maintained for as long as possible during grain filling (Sylvester-Bradley *et al.*, 1996).

2. To achieve a GAI of 5, the crop must attain an adequate capacity for canopy expansion by the onset of stem extension. We initially expressed this in terms of a GAI of 2 at GS31.

3. An amount of soil N equivalent to that measured as mineral N in the top 90cm of soil in late February will be recovered by harvest. Most of this will be taken up by anthesis (Vaidynathan *et al*. 1987), when canopies reach their maximum size (Willington *et al*., 1982).

4. To prevent unnecessarily early applications, it was proposed that the crop should have about 1.5 leaves per mainstem before any N was applied, or crop demand would be too small for effective N recovery.

5. Before the crops reach GS 31, it was assumed that their roots would be able to extract N from the top 60 cm of soil only (Gregory, 1979).

6. After the crops reached GS 31, it was assumed that their roots could extract N from the top 90 cm of soil (Gregory, 1979).

7. N in the soil below 90 cm is not accounted for in the calculations. Any N below 90cm was considered to be an insignificant proportion of the total soil N available.

8. Crop GAI is proportional to the amount of N taken up; 1 ha of green area resulting from 30 kg of N uptake (Sylvester-Bradley *et al*., 1990).

9. Applied fertiliser N is assumed to be recovered with 60% efficiency (Bloom *et al*., 1988).

10. After GS 31, the minimum rate of N uptake by the crop will be 2 kg/ha/day (Widdowson, 1979). This rule should ensure sufficient time between application of the final dose of N and the canopy reaching maximum size.

11. The minimum amount of granular ammonium nitrate fertiliser that can practically be applied is equivalent to 30 kg/ha N.

12. If the soil is dry, foliar N is necessary to ensure adequate N recovery (Powlson, *et al*. 1979; Kettlewell, pers. com.). Foliar N should be applied as an aqueous solution of urea at 30 kg N in 300 l/ha in two applications of 15 kg/ha applied 7 days apart, in order to avoid leaf scorch.

Comparing Canopy Management with conventional practices

This project was set up to compare crop performance using conventional N fertilisation with that based on the achievement of an optimum canopy size with late N applied to maintain canopy duration (Canopy Management). It was clear at the outset that the two systems would differ in both amount and timing of N; it would not be possible to analyse each and every difference between the two systems. Thus, it was necessary to take a 'systems approach' when making the comparisons. The two systems were compared in economic terms, taking both grain yield and quality into account.

However, it was possible to explore the most crucial differences between the two systems using two additional treatments and a range of additional measurements.

(i) Unfertilised crops were used to determine the recovery of soil and fertiliser N.

(ii) N response experiments were set up to provide conventionally determined N optima.

(iii) Detailed measurements were taken to interpret performance (eg measurements of canopy size and the amount of sunlight intercepted). These measurements were mainly used to test whether the individual components of the proposed framework between N application and yield formation were sufficiently robust to hold for wheat grown over a wide range of conditions.

Thus the tests of Canopy Management had two main objectives :

1. An examination of the adequacy of the proposed rules for managing canopies with N. i.e. Were the rules sufficiently robust to be developed into farmer-friendly guidelines ? and,
2. Assessment of whether a management system based on these rules would produce equivalent grain yield and quality, with no greater use of N, than a more conventional N management system.

There were three operations within the research project :

- **Field tests of Canopy Management** - A large programme of field experiments to test the rules for and outcome of Canopy Management. Participants were ADAS, The University of Nottingham, Arable Research Centres, Harper Adams Agricultural College and SAC Edinburgh.
- **Improving the efficacy of late N** - A series of field experiments designed to identify the conditions under which late application of foliar N is likely to be most effective. This part of the project was undertaken at IACR Rothamsted.
- **Milling and Baking quality** - Grain samples were taken from selected treatments of the Field Tests and full milling and baking tests were conducted. This part of the project was undertaken by staff at Camden and Chorleywood Food Research Association (CCFRA).

The report is structured so as to address the two underlying principles of the Canopy Management approach. It does this through presentation of all the experimental evidence collected so as to allow examination each of the component steps in the theoretical framework shown in Figure 2.

These steps are:
N uptake -
- soil mineral N
- fertiliser N

Canopy expansion -
Light interception -
Biomass production -
Biomass redistribution, grain formation and yield -

Nitrogen redistribution and grain quality -
Economics of Canopy Management -

In order to examine all the experimental work conducted in this programme on Canopy Management and to maintain a logical sequence, the above structure will encompass all the evidence coming from the field tests, the work on foliar N at IACR Rothamsted and the analyses of grain quality at CCFRA. To avoid potential confusion, the field tests of the rules and target for Canopy Management be described as the *field tests*. Work originating from IACR Rothamsted will be described as the *Rothamsted* work and the analyses at CCFRA will be described as the *CCFRA* work

Materials and methods

1. The field tests of Canopy Management

The field tests of Canopy Management comprised a large experimental programme conducted over three winter wheat harvest years, 1993, 1994 and 1995 at a range of sites in England and Scotland. The aim was to test the Canopy Management approach to N fertilisation against conventional practice (MAFF, 1994) across the breadth of growing conditions likely to be found in commercial practise. Sites were chosen to provide crops with high and low yield potential, judged according to influences of soil type and rainfall pattern. Four sites were used in the first season but this increased, to provide a wider testbed, to six and eight in the second and third experimental seasons respectively. The soil types at each of the experimental sites are shown in Table 1.

Table 1 The soil types at the experimental sites

Site	Location	1993	1994	1995
ADAS Boxworth	Cambridgeshire	Clay loam	Clay loam	Clay loam
University of Nottingham	Nottinghamshire	Sandy loam over Keuper Marl	Silty clay loam	Alluvial
ADAS Terrington	Norfolk	Silty clay loam	Silty clay loam	Silty clay loam
ADAS Rosemaund	Herefordshire	Silt loam	Silt loam	Silt loam
Arable Research Centres Cirencester	Gloucestershire		Shallow clay brash	Clay loam
Harper Adams Agricultural College	Shropshire		Sandy clay loam	Sandy clay loam
ADAS High Mowthorpe	North Yorkshire			Shallow stony silt loam
SAC Edinburgh	Lothians			Alluvial

Variation in crop condition (forwardness, backwardness, greenness, tiller number etc) was manipulated further by sowing early or late into soils with contrasting residues of N. The aim was to drill early sowings in the last week of September or first week of October and late sowings at least five weeks later. However, this was not always possible because poor weather conditions during seedbed preparation or drilling sometimes necessitated delays to improve the chances of establishing a uniform population of about 275 plants m^{-2} in spring. Differences in residual N were produced by application of fertiliser N to the preceding break crop. The difference in N applied was 200 kg/ha N before 1993 and 1994, but this difference was increased to 300 kg/ha N for the break crop preceding the experimental crop harvested in 1995.

Throughout testing, the variety Mercia was used. At the outset, it was a popular variety with good breadmaking potential (NIAB, 1996) and it was widely adopted in other HGCA funded research. Thus there was potential to build a substantial data set which could be compared with data from contemporary experiments. For this reason, the methodologies reported here were, as far as possible, standardised with those of other HGCA funded experiments so as to minimise differences in experimental technique.

Factorial combinations of 'early' and 'late' sowing with 'high' and 'low' soil N residue were set up in all years at ADAS Boxworth, University of Nottingham and ADAS Terrington. At the other sites, *either* early and late sowings were compared on a low N residue soil, *or* high and low N resides were compared with just early sowings.

For brevity, early and late sowings will be referred to as ES and LS respectively and high and low N residues will be referred to as HN and LN respectively. Thus, LNES represents an early sowing into a soil where the preceding break crop received the smaller application of N. Table 2 summarises the manipulation to crop condition in each year.

Table 2 Manipulation of crop condition in each year of the field tests of Canopy Management

Site	Location	1993	1994	1995
ADAS Boxworth	Cambridgeshire	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS
University of Nottingham	Nottinghamshire	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS
ADAS Terrington	Norfolk	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS	HNES, HNLS, LNES, LNLS
ADAS Rosemaund	Herefordshire	HNES, LNES	HNES, LNES	HNES, LNES
Arable Research Centres Cirencester	Gloucestershire		LNES, LNLS	LNES, LNLS
Harper Adams Agricultural College	Shropshire		LNES, LNLS	LNES, LNLS
ADAS High Mowthorpe	North Yorkshire			HNES, LNES
SAC Edinburgh	Lothians			LNES, LNLS

Details of the preceding crop, N application to the preceding crop and the date of sowing at each of the sites for the wheat harvest years 1993, 1994 and 1995 are presented Table 3, Table 4, and Table 5 respectively. The treatments listed provided the 'background' crops against each of which Canopy Management and conventional practice were tested. In the first season, Canopy Management was tested as a single treatment (N was applied to produce a maximum green area index of 5 (‘GAI 5’) with 60kg/ha N applied at anthesis (GAI 5+). In subsequent seasons, Canopy Management *with* (GAI 5+) and *without* (GAI 5-) late N at flowering (60 kg/ha) were both compared with conventional N use to investigate whether any benefits from Canopy Management arose through restricting canopy size early in the season as distinct from prolonging canopy size during the grain filling period.

There were therefore 14 tests of Canopy Management in 1993, 16 tests in 1994 (the late sowings at ADAS Terrington had to be abandoned due to exceptionally poor establishment following prolonged water logging) and 22 tests in 1995 giving a total of 52 tests where late N at flowering was applied and 38 tests where late N was not applied.

Additionally in each year at ADAS Boxworth, University of Nottingham and ADAS Terrington, a further experiment was conducted to determine the optimum amount of N for yield, to check how close conventional N use was to the optimum. With the exception of the University of Nottingham in 1995 (when crop response to increasing amounts of N was tested on all combinations of sowing date and soil N residue), crop response to increasing N could only be tested for the early sown crops grown on the low N residue soils (LNES). In these N response tests, the crops were established and managed identically to those in the Canopy Management tests.

All crops were sown after ploughing and appropriate secondary cultivation to produce a suitable seedbed. Seed was dressed with Rappor and seed rates were adjusted according to seed size and local experience of field conditions, including expected overwinter losses, with the aim of achieving 275 m^2 established plants in spring. Seeds were sown 2-4cm deep in rows 12 - 15 cm wide in plots at least 24m by 6m. The two sowing dates, the two N residues or their four combinations formed mainplots (referred hereafter to as 'background crops') and the Canopy Management treatments formed subplots at all sites except ADAS Rosemaund. Here, N residue ('background crop') and Canopy Management combinations were fully randomised. At all sites, there were three replicates of each Canopy Management comparison with conventional N

All crops were managed to limit weeds, pests and diseases to very low levels. Prophylactic use of appropriate proprietary products were used following manufacturers' recommendation. The fungicide regime was based on tebuconazole. The need for crop protection was determined for the most high risk plot and applications were made to all treatments within a site. Unless local knowledge suggested lodging risk was minimal, Chlormequat (Chlormequat + Choline Chloride) at GS 30/31 and Terpal (Ethephon + Mepiquat Chloride) at GS 32/37 were usually used in combination, following manufacturers' recommendation to minimise the risk of lodging. Where PGR use was necessary, all plots within a site were treated.

Table 3 Details of the proceeding crop, N application to proceeding crop and sowing date of the test crops for Canopy Management in 1993.

Site and previous crop	N applied to previous crop (kg/ha)	Sowing date
ADAS Boxworth (spring oilseed rape)		
HNES	250	1 October 1992
HNLS	250	5 November 1992
LNES	50	1 October 1992
LNLS	50	5 November 1992
University of Nottingham (whole crop winter oats)		
HNES	200	7 October 1992
HNLS	200	14 December 1992
LNES	0	7 October 1992
LNLS	0	14 December 1992
ADAS Terrington (potatoes)		
HNES	250	15 October 1992
HNLS	250	18 January 1993
LNES	50	15 October 1992
LNLS	50	18 January 1993
ADAS Rosemaund (winter oilseed rape)		
HNES	250	16 October 1992
LNES	50	16 October 1992

Table 4 Details of the proceeding crop, N application to proceeding crop and sowing date of the test crops for Canopy Management in 1994.

Site and previous crop	N applied to previous crop (kg/ha)	Sowing date
ADAS Boxworth (spring oilseed rape)		
HNES	250	18 October 1993
HNLS	250	29 November 1993
LNES	50	18 October 1993
LNLS	50	29 November 1993
University of Nottingham (winter oilseed rape)		
HNES	200	2 November 1993
HNLS	200	7 March 1994
LNES	0	2 November 1993
LNLS	0	7 March 1994
ADAS Terrington (potatoes)		
HNES	250	8 October 1993
HNLS	250	9 November 1993
LNES	50	8 October 1993
LNLS	50	9 November 1993
ADAS Rosemaund (winter oilseed rape)		
HNES	250	20 October 1993
LNES	50	20 October 1993
Arable Research Centres Cirencester (winter oilseed rape)		
LNES	134	19 October 1993
LNLS	134	23 November 1993
Harper Adams Agricultural College (winter oats)		
LNES	unknown	28 September 1993
LNLS	unknown	8 November 1993

Table 5 Details of the proceeding crop, N application to proceeding crop and sowing date of the test crops for Canopy Management in 1995.

Site and previous crop		N applied to previous crop (kg/ha)	Sowing date
ADAS Boxworth (winter oilseed rape)			
	HNES	300	6 October 1994
	HNLS	300	15 November 1994
	LNES	0	6 October 1994
	LNLS	0	15 November 1994
University of Nottingham (whole crop winter oats)			
	HNES	300	6 October 1994
	HNLS	300	15 November 1994
	LNES	0	6 October 1994
	LNLS	0	15 November 1994
ADAS Terrington (potatoes)			
	HNES	350	26 September 1994
	HNLS	350	1 November 1994
	LNES	50	26 September 1994
	LNLS	50	1 November 1994
ADAS Rosemaund (spring oilseed rape)			
	HNES	330	30 September 1994
	LNES	30	30 September 1994
Arable Research Centres Cirencester (winter oilseed rape)			
	LNES	225	30 September 1994
	LNLS	225	27 October 1994
Harper Adams Agricultural College (spring oilseed rape)			
	LNES	300	5 October 1994
	LNLS	300	2 November 1994
ADAS High Mowthorpe (winter oilseed rape)			
	HNES	300	28 September 1994
	LNES	0	28 September 1994
SAC Edinburgh (winter barley)			
	LNES	180	23 September 1994
	LNLS	180	7 November 1994

Spring Nitrogen treatments.

Conventional

N was applied in spring according to published recommendations (MAFF, 1994) modified according to local commercial practice. The total quantity of N for early sowings with small N residues was set at 220 kg/ha where, from past performance at the site, it was reasonable to expect 9t/ha grain yield. At lower yielding sites this total was reduced by 20 kg/ha per tonne. A reduction of 10 kg/ha was made for late sowings on account of their smaller expected yield and, with large N residues, there was a further reduction of about 50 kg/ha on heavy soils and about 20 kg/ha on light or shallow soils. This calculated total N dose was then split, with 30 kg/ha being applied in early March and the remainder when the 'first node detectable' (Tottman, 1987) stage was reached, normally during April.

Canopy Management

Canopy size and crop N uptake (kg/ha) were measured in late February (see later for methods). At the same time, soil was sampled in 30cm layers down to 90cm and mineral N determined (MAFF, 1994). Mineral N in each layer was calculated assuming a bulk density of 1.3 and each 30kg/ha was assumed to provide for expansion of 1 unit of GAI. N requirement was set at 50 kg N per ha of shortfall in expected canopy size (60% recovery) from the supply from soil (total mineral N in top 90cm) plus the N already in the crop. Where crop uptake plus anticipated N supply (mineral N in top 60cm) was judged insufficient to provide for 60 kg/ha of N uptake (GAI 2) by GS 31, 30 - 50 kg/ha of fertiliser N was applied in March to promote tillering. If the balance of N, required for uptake of 150 kg/ha, was larger than 50 kg/ha, it was applied in two doses split about 60:40 and applied allowing for a rate of uptake of 2 kg/ha /day before maximum canopy size was anticipated (early June). N to prolong canopy size was applied at anthesis either as granular N if soils were moist or rain expected in the following 5 days, or as foliar urea applied in two equal doses seven days apart to reduce the risk of leaf scorch.

For example:

if crop N in Feb = 30 kg/ha and,

soil mineral N in top 90cm = 90 kg/ha

then 30 kg is already in the crop plus 100% * 90 kg/ha = 120 kg/ha for canopy expansion

then fertiliser N for 30 kg/ha (150 - 120) uptake is required
if fertiliser N is recovered with 60% efficiency, 50 kg/ha will need to be applied
timing the application of 50 kg/ha N would be determined by the 'rules', allowing 15 - 20 days (uptake of 30 kg/ha at 2 kg/ha/day) before maximum canopy size.

Details of the amounts and timings of the applications to the conventional and Canopy Management treatments in the field tests of Canopy Management are presented in Table 6, Table 7, and Table 8 respectively.

Application

All applications of N to produce the target canopy size were of granular ammonium nitrate applied uniformly by hand. Granular applications at anthesis were also ammonium nitrate.

Nil N

In all years, all comparisons of Canopy Management and conventional N were grown along side crops which did not receive spring fertiliser N. These crops were used to determine soil N supply.

Table 6 Details of the spring applications of fertiliser N in the tests of Canopy Management in 1993 (kg/ha).

	Conventional N			Canopy Management N				
ADAS Boxworth	8 Mar	21 Apr	***Total***	21 Apr	10 May		15 June	***Total***
HNES	30	110	***140***	40			60	***100***
HNLS	30	100	***130***	30			60	***90***
LNES	30	160	***190***	40	30		60	***130***
LNLS	30	150	***180***	40	30		60	***130***
University of Nottingham	12 Mar	26 Apr	***Total***	30 Mar	26 Apr	14 May	10 Jun	***Total***
HNES	30	160	***190***	30	50	30	60	***170***
HNLS	30	150	***180***	30	30	30	60	***150***
LNES	30	180	***210***	30	70	30	60	***190***
LNLS	30	170	***200***	30	60	30	60	***180***
ADAS Terrington	11 Mar	21 Apr	***Total***	11 Mar	21 Apr	21 May	18 Jun	***Total***
HNES	90	40	***130***	90	30		60	***180***
HNLS	90	30	***120***	60	30	30	60	***180***
LNES	90	90	***180***	90	30		60	***180***
LNLS	90	80	***170***	60	40	30	60	***190***
ADAS Rosemaund	12 Mar	19 Apr	***Total***	12 Mar	19 Apr	13 May	17 Jun	***Total***
HNES	30	120	***150***		70	30	60	***160***
LNES	30	170	***200***	30	80	30	60	***200***

Table 7 Details of the spring applications of fertiliser N in the tests of Canopy Management in spring 1994 (kg/ha). * = foliar urea applied in two doses of 30 kg/ha N at anthesis and 1 week later.

	Conventional N			Canopy management N				
ADAS Boxworth	10 Mar	22 Apr	***Total***	30 Mar	22 Apr	13 May	Anthesis	***Total***
HNES	30	110	***140***		60	30	60	***150***
HNLS	30	100	***130***		60	30	60	***150***
LNES	30	160	***190***	30	60	50	60	***200***
LNLS	30	150	***180***		70	50	60	***180***
University of Nottingham	11 Mar	18 Apr	***Total***	28 mar	18 Apr	9 May	Anthesis	***Total***
HNES	30	140	***170***		70		60	***130***
LNES	30	160	***190***		50	50	60	***160***
	18 Apr	9 May	***Total***	28 mar	18 Apr	9 May	Anthesis	***Total***
HNLS	30	130	***160***		60		60	***120***
LNLS	30	150	***180***		50	60	60	***170***
ADAS Terrington	10 Mar	22 Apr	***Total***	5 Apr	22 Apr	10 May	Anthesis	***Total***
HNES	30	100	***130***	30	70	30	60*	***190***
LNES	30	150	***180***	40	70	30	60*	***200***
ADAS Rosemaund	10 Mar	18 Apr	***Total***		18 Apr		Anthesis	***Total***
HNES	30	120	***150***		30		60	***90***
LNES	30	170	***200***		50		60	***110***
ARC Cirencester	17 Mar	22 Apr	***Total***	30 Mar	22 Apr	11 May	Anthesis	***Total***
LNES	30	170	***200***	30	30	30	60	***150***
LNLS	30	160	***190***	30	30	50	60	***170***
HAA College	21 Mar	18 Apr	***Total***	6 Apr	18 Apr		Anthesis	***Total***
LNES	30	170	***200***	30	110		60*	***200***
LNLS	30	160	***190***	30	120		60*	***210***

Table 8 Details of the spring applications of fertiliser N in the tests of Canopy Management in spring 1995 (kg/ha). * = foliar urea applied in two doses of 30 kg/ha N at anthesis and 1 week later.

	Conventional N			Canopy Management N					
ADAS Boxworth	13 Mar	GS 31	***Total***	13 Mar	30 Mar	GS 31	7 May	Anthesis	***Total***
HNES	30	110	***140***	30		60	50	60	***200***
HNLS	30	100	***130***			60		60	***120***
LNES	30	160	***190***		30	90	60	60	***240***
LNLS	30	150	***180***			60		60	***120***
U of Nottingham		GS 31	***Total***		30 Mar	GS 31	7 May	Anthesis	***Total***
HNES	30	130	***160***			80		60*	***140***
HNLS	30	120	***150***		30	80		60*	***170***
LNES	30	160	***190***		30	100	40	60*	***230***
LNLS	30	150	***180***		30	100	40	60*	***230***
ADAS Terrington		GS 31	***Total***	17 Mar	30 Mar	GS 31	5 May	Anthesis	***Total***
HNES	30	90	***120***					60	***60***
HNLS	30	90	***120***					60	***60***
LNES	30	150	***180***	30		70	30	60	***190***
LNLS	30	140	***170***	30		90	30	60	***210***
ADAS Rosemaund		GS 31	***Total***		30 Mar	GS 31	5 May	Anthesis	***Total***
HNES	30	120	***150***				50	60	***110***
LNES	30	170	***200***		80			60	***140***
ARC Cirencester		GS 31	***Total***		30 mar	GS 31	10 May	Anthesis	***Total***
LNES	30	170	***200***		30	90		60	***180***
LNLS	30	160	***190***		30	100		60	***190***
HAA College		GS 31	***Total***	17 Mar	31 Mar	GS 31		Anthesis	***Total***
LNES	30	170	***200***	30	30	90		60	***210***
LNLS	30	160	***190***	30	30	100		60	***220***
ADAS H Mowthorpe		GS 31	***Total***			GS 31	10 May	Anthesis	***Total***
HNES	30	170	***200***			90	75	60*	***225***
LNES	30	190	***220***			100	75	60*	***235***
SAC Edinburgh		GS 31	***Total***		31 Mar	GS 31	18 May	Anthesis	***Total***
LNES	30	170	***200***		30	100	60	60	***250***
LNLS	30	160	***190***		30	90	60	60	***240***

Crop measurements at ADAS Boxworth and the University of Nottingham

Analyses of growth

The experiments at ADAS Boxworth and the University of Nottingham were monitored in most detail. It was not possible with the resources available to make detailed measurements at other sites. Crop dry matter and partitioning to ears, crop N uptake and partitioning to ears, crop green area and shoot number were measured fortnightly using the following protocol.

Sampling in the field

To avoid bias in their selection, samples were taken from predetermined areas; quadrats (1.2m * 0.6m {0.72m^2}) were placed into the plots before the start of early spring growth. These were orientated such that opposite diagonal corners of the quadrat were placed in the same drill row to ensure the number of rows covered by the quadrat did not vary (this can happen if quadrats are oriented with edges parallel to the drill rows). At least 50cm discard was left between adjacent quadrats and from the edge of the plot. Sampling was conducted systematically through the length of the plot to eliminate the risk of previously disturbed areas of crop being sampled on future occasions. In order to reduce any risk of bias through plots varying along their length, two replicates of the three were sampled from the opposite end to the third replicate.

Sample removal

The objective was to recover all the above ground material within the quadrat including any dying and dead material. Sharp scissors or secateurs were used to cut the plants at soil surface. All the cut material was collected and placed as quickly as possible into a plastic bag which was then sealed. After stem extension, the stems were placed into bags so that the lower portion (most contaminated with soil) was at the bottom to reduce the amount of crop contaminated with soil and hence minimise the time spent washing. When sampling at the University of Nottingham, and especially when conditions were hot, sample were removed to a cold store (4 - 6 ^{o}C) once a replicate block had been sampled. At ADAS Boxworth, this was not possible and samples were removed from direct sunlight and stored wherever coolest. On return to the laboratory at the University of Nottingham, sample bags were transferred as quickly as possible to a cold store and kept at 4 - 6 ^{o}C to prevent deterioration. All analyses of growth were made within 4-5 days of sampling.

If the plant material was contaminated with soil, samples were washed immediately before analyses; it was found that washing followed by further cold storage hastened deterioration of the green lamina surface.

Analyses in the laboratory

All the plant material was removed from the bag. If the samples were contaminated with soil, they were gently washed under a running tap. Paper towel was used to remove all surface water from the sample. The clean plant material was spread out and about 10 - 15% was chosen at random for analyses of growth. As quickly as possible, the fresh weights of the total sample and sub-sample were recorded. Frequently, checks for bias in the sub-sample were made by comparing the size distribution of the shoots in the subsample with that in the remainder of the total. If the sub-sample did not appear to be representative, it was returned, remixed and a second sample taken.

In the early stages of crop growth, all of the remaining plant material from the field sample (after removal of the sub sample for growth analysis) was dried at 80^{o}C until constant weight was reached. Later in the season when samples were larger, a second sub sample was taken and this was split into ears and stem (including green and dead laminae) this was dried to constant weight and sent to ADAS Wolverhampton for analysis of total N by the Dumas method (MAFF, 1994). The sub sample for growth analysis was split into potentially fertile shoots (when its prophyl or first leaf had emerged from the subtending leaf sheath on its mother shoot) and potentially infertile shoots (when its newest expanding leaf had begun to turn yellow at the tip and/or its flag leaf was fully emerged but there was no evidence of ear swelling).

For the group of shoots identified as potentially fertile, the material was separated into green lamina, green true stem plus sheath, ear, non-green stem plus sheath (non-green but not dead) and dead material (dead lamina). If the ear was partially emerged from flag leaf sheath, the exposed portion was cut off if a cut could be made perpendicular to the rachis. If only one side of the ear was visible i.e. it was starting to burst through the side of the flag leaf sheath, the ear was included with the stem and leaf sheath portion. The projected areas of the green lamina, green true stem and ear were recorded using a Licor 4000 planimeter (MAFF, 1994). When the ear had begun to senesce, the percentage of the ear which was green was determined by eye and the total area of ears adjusted to give the green area. After the projected areas had been determined, the dry weights were determined.

Analyses at crop maturity

Shortly before harvesting, quadrat samples were taken and the following determined; total above ground biomass and yields of grain chaff and straw, ear number, grain number, mean grain size, total N offtake and offtake in grain, chaff and straw.
In the laboratory, all ears were cut off at the peduncle and the fresh weight of straw was recorded. A 10-15% sub sample was taken for determination of straw moisture content and N%. All the ears were counted. After threshing, all the grain and chaff was recovered and the dry weights recorded.

In addition to the quadrat samples, samples of plants from along the length of the combine strip were taken immediately before combining. Five random grab samples (abut 100 ears) were taken and bulked together in a paper sack. In the laboratory, these were allowed to begin to dry. If samples were wet, they were force dried using an on-farm air duct drier. During analysis, all the roots were removed at ground level. The ears were cut off and threshed, collect all grain and chaff. The dry weights of all the straw, chaff and grain were recorded and samples were analysed for total N% (MAFF, 1994).

Combine harvesting

Plots were harvested by staff at each Centre using plot combines (normally Sampo Rosenlew models). Prior to harvesting, tramlines were cut out so these did not form part of the harvested area (the tramlines ran perpendicular to the long axis of the plot). This left two or three lengths of crop for harvesting. The lengths of these were measured accurately and the width of the combine cut was measured after cutting. A combine strip was taken through the centre of the half of the plot from which no previous samples had been taken (except for the grab samples). The combines were set to produce a relatively 'clean' grain sample whilst minimising loss of grain. The total grain harvested was recorded and an 8 kg sample taken. About 0.5 kg was removed from this sample and sealed in a plastic bag and sent immediately to ADAS Wolverhampton for analyses for moisture content, screenings, mean grain size, Hagberg Falling Number, Specific weight and N% (MAFF, 1994). The remaining 7.5 kg of grain was air dried if necessary and stored in cool dry conditions ready for baking tests.

Analyses of soil mineral N

In early February, at anthesis and maturity, six soil cores per plot were taken to rock or 90cm and the layers 0-30cm, 30-60cm and 60-90 cm were kept separate. Bulked samples for each of the horizons were frozen (-18^{o}C) and sent frozen to ADAS Woverhampton for analyses of dry matter, ammonium N and nitrate N.

Interception of sunlight

In all plots at ADAS Boxworth and the University of Nottingham, tube solarimeters (Seicz, et al., 1964) were installed at the base of the crop. Output from these was continuously monitored using a data logger and was compared with output from two above crop reference solarimeters to allow fractional interception of sunlight to be calculated.

Measurement of light attenuation (k)

At the University of Nottingham in 1994, measurements of canopy architecture were made in the conventional N and nil N plots in the early sowing at the low N residue. In each plot, the measurement of photosynthetically active radiation (PAR) was made by using a ceptometer. PAR was measured above, below and at designated layers within the canopy. Each replicate set of readings was taken from a different area of the crop for readings to be as representative as possible of the whole plot. The ceptometer was placed at 90° to the direction of the crop rows. On the days when the canopy was sampled, a set of readings was taken from the sampled area. The ceptometer was placed on clips secured to a vertical pole at 10 cm intervals in height from the top of the canopy. Readings were taken from above the canopy and then at intervals of 10 cm until the soil surface was reached.

Stratified clips of plant material were taken every two weeks from a 0.72 m^2 quadrat mounted on three legs. The quadrat could be moved up and down so that it could be supported at the base of each 10cm layer. The crop was sequentially harvested in 10cm layers down the canopy, the base of each layer coinciding with where measurements made with the ceptometer. The lowest layer was normally less than 10 cm in height but was harvested in the same way as the other layers. The harvested material from each layer was placed in a plastic bag and stored in a cold room prior to analysis.

The projected areas of the components of the canopy were made on a random sub-sample of about 20% of the plant material from each of the layers. The sample was split into the green leaf, green stem, green sheath and ear as well as dead leaf, dead stem and dead sheath. The projected area of each individual component was measured by using an electronic planimeter.

Crop measurements at other sites

At ADAS Terrington, ADAS Rosemaund, Arable Research Centres Cirencester, Harper Adams Agricultural College, ADAS High Mowthorpe and SAC Edinburgh, soil N and crop size and N content was measured in February (as at ADAS Boxworth and the University of Nottingham). A few measurements were made during the growing season in an attempt to explain performance at final harvest. Combine yields and grab samples were taken at harvest.

2. Foliar N studies at IACR Rothamsted

The aim of the work conducted at IACR Rothamsted was to examine the possible reasons for the generally poorer than expected recovery of granular or foliar applications of fertiliser N made late in the season to prolong canopy duration. Field and controlled environment experiments were conducted.

Field experiments

Three field experiments were conducted, two at IACR-Rothamsted, Hertfordshire, during 1994 and 1995 harvest seasons and one at the University of Nottingham in 1995. At each site, a range of N treatments was set up and additional N treatments were applied as either foliar urea or granular ammonium nitrate.
Winter wheat cv. Mercia was sown at a rate of 380 seeds m^{-2} into soils with non-limiting phosphorous and potassium contents. The soil at IACR-Rothamsted is a

flinty silt loam / loam over clay with flints of the Batcombe series; at the University of Nottingham the site had an alluvial soil of the Fladbury series.

Spring nitrogen treatments

Spring N was applied to form contrasting sizes of crop canopy to which additional fertiliser N applications were made to examine for effects on canopy prolongation.

1. A conventionally fertilised 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.
2. Spring N was not applied (nil N)
3. Fertiliser N was applied to provide for a canopy of GAI 5 by ear emergence .
4. Fertiliser N was applied to provide for a canopy of GAI 3 by ear emergence .

A combination of some or all of these treatments was used in the three experiments. The amount of N applied to the GAI 5 and GAI 3 target canopies was determined using the rules for Canopy Management listed in the introduction of this report .

Field experiment at IACR-Rothamsted 1994

The experiment was arranged in three randomised blocks of 8 main plot N treatments, with early and late sowings (24 September and 19 October 1993). The previous crop was winter oats to which 60 kg/ha N had been applied to provide soil with a low N residue (25 and 31 kg/ha N respectively for the early and late sowings). The conventional application of N was determined using the soil mineral N content in February and the estimated uptake of the crop and adjusted for expected yield. N was applied as nitro-chalk, (calcium nitrate $Ca(NO_3)_2$), 27 % N, as a split dressing of 60 kg/ha N on 6 April 1994, 30 kg/ha N to the GAI 3 treatment and the balance on 28 April 1994. The amounts of fertiliser N applied to form the contrasting canopies on which the effect of additional applications of N were tested are shown in Table 9.

Table 9 Fertiliser N applied at IACR-Rothamsted 1994

Treatment	N Applied (kg/ha)
Nil N	0
Conventional N	265
GAI 5	200
GAI 3	100

Foliar N applications

Foliar urea was applied at a rate of 40 kg/ha N in 450 l/ha water (85.8 kg/ha of urea) using a Fox petrol driven knapsack sprayer, using a 3 m boom fitted with Lurmark 03-F110 110° flat fan nozzles (red) which gave a medium quality spray. The operating pressure was 2.5 bar with an output of 0.6 l/min applied at 1 m/s (3.6 km/h). The urea was applied in two passes of 20 kg/ha N in 225 l/ ha water.

Foliar N was applied, to the GAI 5 crops, either at flag leaf emergence (GS 39), just prior to ear emergence (GS 51) or at anthesis (GS 65). Also, prior to ear emergence, an application of 40 kg/ha N of late N, was applied by hand, spread evenly over the soil surface, to the GAI 5 treatment (GS 51). Nitro-chalk was used instead of ammonium nitrate because of its lower N content so that a greater mass of fertiliser could be applied to improve the uniformity of application.

Growth Analysis

Destructive samples of crop were taken fortnightly during the growing season from quadrat areas ($0.8m^2$; 0.67m * 10 rows) and dry weights and projected green areas were determined as reported for the field tests of Canopy Management (above). The first sample was taken on 21 March 1994 before the start of stem extension (GS 31), and before the first application of N fertiliser. The first four samples involved the removal of the whole plant including the roots. The root system was washed to remove any soil present and then the whole sample was thoroughly dried using a spin dryer and tissue paper. Total plant and shoot numbers were counted and then the roots were removed and the total fresh weight of the sample without roots was recorded. The measurements made on these samples were total fresh weight, total dry weight, % moisture content, total plant number m^2, total shoot number m^2, number of shoots per plant, projected GAI and projected green area per plant.

The fifth sample was taken on 26 May 1994 just prior to flag leaf emergence (GS 39), and for this and all subsequent samples, the shoots were cut off just above soil level. Two sub-samples were taken for shoot number and GAI determination, and then replaced for measurement of dry weight. The following measurements were made in addition to those made on earlier samples: projected GAI of the whole shoot, leaf, stem and when present, the ear and any dead material
All the samples taken for growth analysis were analysed for total N content.

Stratified canopy measurement of urea deposition

After application of foliar urea, the canopy was cut into stratified sections to determine the site of deposition. Ten stems were taken at random from the plots and bulked together and the heights of the leaves in the canopy were recorded. Then the leaves were removed in order, the flag leaf first, by cutting just above the ligule. Where present, the ear was sampled. After the ear and leaves had been removed, the stem was cut into 10 cm sections from the base upwards. The fresh weight of each sample of ten leaves, ears or stem pieces was recorded. The samples of ten leaves or stem sections were placed in 200 ml of 0.1 % triton X-100 solution to wash off any urea present. The bottles were gently inverted to ensure complete coverage of the plant material. The plant material was removed after ten minutes and the solutions immediately frozen. The green area of all the components of the plant material was measured, and the dry weight and total N content determined.

A complete stratified sample of the crop was made before the urea was applied, immediately after the application of foliar urea (0), and 1, 3, 6, 9, 12, 24, and 48 hours after application. The total N content of the plant samples was measured before urea was applied, and at 6 and 48 hours after application

Hand harvest - yield components

An area of crop 1.2 m^2 (1 m by 10 rows) was sampled. The shoots were cut off above soil level and then placed in a hessian sack and air dried for approximately one week.. The sample was threshed and the dry weight of grain, straw and chaff determined, after drying at 80°C to constant weight

Combine harvest

An area of 30m^2 was harvested using a plot combine set to produce a relatively clean sample but with undue loss of grain. The weight of grain harvested was recorded and a 3 kg sample of grain taken. A 1.5 kg sample of straw was taken.

Grain quality

The quality of the harvested grain samples was determined by measuring screenings, individual seed weight, Hagberg Falling Number and specific weight using standard laboratory methods (MAFF, 1986).

Field experiment at IACR-Rothamsted 1995

The experiment was arranged in four randomised blocks of three N treatments (nil N, conventional N and GAI 5) sown on 21 September 1994. These main plots were subdivided into five sub-plots each receiving different applications of foliar N. The previous crop was winter oats to which 100 kg/ha N was applied; soil mineral N (0-90cm) was 24 kg/ha in the soil in February. The amount of N present in the crop was measured in February as 16 kg/ha N.

The amount of N applied to the conventional N treatment was calculated using the amount of N present in the crop and the soil mineral N (0-90cm) in February, previous cropping history, sowing date and expected yield, as for 1994. N was applied as a split dressing of ammonium nitrate, 34.5 % N, with 30 kg/ha N on 16 March 1995 and the balance on 12 April 1995. Applications for the GAI 5 treatment were determined using the rules set out in the introduction to this report. The amount of N applied to form the contrasting canopies on which the effects of further, later applications of N were tested are shown in Table 10

Table 10 Fertiliser N applied at IACR-Rothamsted 1994/1995.

Treatment	N Applied (kg/ha)
Nil N	0

Conventional N	200
GAI 5	120

Foliar urea treatments

Foliar urea was applied to the above treatments using a CO_2 pressurised knapsack sprayer. The 3 m spray boom was held 0.5 m above the crop surface and urea was applied using Lurmark 03-F110 110° flat fan nozzles, producing a medium quality spray, at 3.0 bar pressure, with an output of 0.542 l/min at 0.625 m/s[1] (2.25 km/h). The time taken to spray a 4 m plot was 6.4s.

Foliar urea treatments were applied at different times during the growing season and at two different rates to enable the assessment of the most effective method of prolonging the GAI of the canopy and to provide information on the dynamics of uptake of foliarly applied urea. A range of adjuvants was also tested. These were a spreader, (Silwet L-77), a sticker, (Spray-Fix) and a penetrant (LI-700), all supplied by Newman Agrochemicals, Cambridge. Urea N was applied at 30 kg/ha in 400 l/ha with a 0.1 % solution of the adjuvant (1 ml/litre). Each adjuvant was applied at ear emergence. The spreader was applied a second time during anthesis as the visible urea deposits on leaf after application at ear emergence appeared to be much greater than the deposits from the other adjuvants. The treatments applied are summarised in Table 11 .

Growth analysis

Samples were taken at tillering (GS 22), the start of stem extension and at flag leaf emergence and were analysed using the methodology used in 1994.

Table 11 Late N applications in the 1995 field experiment at IACR-Rothamsted.

Date of treatment	Treatment	Target Canopy size	Timing
16.5.95[1]	30 kg/ha N	GAI 5	flag leaf emergence
26.5.95	30 kg/ha N[1]	GAI 5	ear emergence
1.6.95	30 kg/ha N + spreader	GAI 5	ear emergence

2.6.95	30 kg/ha N + sticker	GAI 5	ear emergence
2.6.95	30 kg/ha N + penetrant	GAI 5	ear emergence
8.6.95	30 kg/ha N	GAI 5	anthesis
13.6.95	30 kg/ha N	Nil N	anthesis
13.6.95[2]	30 kg/ha N	Conventional N	anthesis
14.6.95	60 kg/ha N	GAI 5	anthesis
15.6.95	30 kg/ha N + spreader	GAI 5	anthesis
-	no extra N applied	GAI 5	-
-	no extra N applied	Nil N	-
-	no extra N applied	Conventional N	-

[1] Treatment was not sampled

[2] An additional 50 kg/ha N, as prilled ammonium nitrate was applied by hand on 25 May 1995 to ensure that the conventionally fertilised canopy was over supplied with N compared to a crop grown to a GAI 5 and therefore subject to luxury uptake.

Stratified canopy measurement of urea deposition

After foliar urea had been applied, a total of ten stems were removed individually from the crop. Care was taken to handle the plant material as little as possible. The ear, when present, and each leaf were cut off directly into 200 ml of 0.1 % triton X-100 solution. The stem was cut into two halves and then cut into shorter pieces and the two halves placed in separate bottles. The bottles were gently inverted to ensure complete coverage of the plant material, which was removed after ten minutes. The area of the plant samples was measured, the dry weight determined and the samples analysed for total N content. The height of each leaf and the ear in the canopy and the length of the stem was measured non-destructively in the remaining crop. A complete stratified sample was made immediately after the urea had been applied and again at the end of the experiment at 96 hours. At intervening time periods, 4, 8, 24, 48, and 72 hours after the application of urea, ten flag leaves only were removed and washed in 200 ml of 0.1 % triton X-100, to determine the dynamics of the loss of urea from the surface of the leaf.

Hand harvest - yield components

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. The grain samples were passed through a 2.2 mm mesh sieve to remove pieces of chaff and broken grain and the weight of the cleaned grain recorded. The number of grains in the sample was counted and grain weight and thousand grain weight calculated.

Assessment of canopy survival

Daily, visual assessments were made of the percentage of the canopy that remained green, from 17 July to 27 July 1995. The whole plot was examined and the percentage of each leaf that was still green was recorded. A hand held Chlorophyll meter SPAD-502 (Minolta, Japan) was used to measure the chlorophyll content (greenness) of the flag leaves. The results were used to obtain an indirect measure of the N content of the crop leaf. The data produced by the chlorophyll meter corresponded to the amount of chlorophyll present in the leaf, calculated from the amount of light transmitted by the leaf. The value obtained for each replicate plot was the mean of 30 readings taken from individual flag leaves. Readings were taken by placing the measuring head of the SPAD meter in the middle of the leaf lamina taking care to avoid the midrib and the leaf tip. One reading was taken per leaf.

Measurement of light interception - ceptometer measurements

Ceptometers were used to measure the proportion of sunlight intercepted by the crop. Measurements were made above the crop to record the total amount of incident radiation and then at 10 cm height intervals from soil upwards. The measurements provided a snapshot of the radiation profile within the crop canopy. As far as was possible, measurements made during the season were taken on days with a similar amount of cloud cover.

Field experiment at the University of Nottingham 1995

The experiment consisted of 12 treatments replicated in three randomised blocks. Foliar application of urea were applied to crops with contrasting canopy size created through differential N application (Table 12). N was applied as split dressing of granular ammonium nitrate on 4 April 1995 with the balance applied on 28 April 1995.

Table 12 N applied at the University of Nottingham in 1995.

Treatment	N Applied (kg/ha)
Nil N	0
Conventional	175
GAI 3	30
GAI 5	120

Foliar urea treatments

Foliar urea was applied to the above treatments using a tractor mounted hydraulic sprayer. A total of 60 kg/ha N was applied during anthesis as two applications of 30 kg/ha in 400 l/ha water on 20 and 27 June 1995. For the purposes of assessment of urea deposition, only one of the spray applications was measured, on the 20 June 1995 to the Nil N, conventionally fertilised and to the Canopy Managed crop (GAI 5). The same rate of prilled ammonium nitrate was also applied on the same occasions to some of the plots. A detailed list of the treatments applied is shown in Table 13.

Table 13 Treatments applied to the 1995 field experiment at the University of Nottingham

Treatment	Target Canopy	Timing
no extra N applied	Nil N	-
60 kg/ha N prilled ammonium nitrate	Nil N	anthesis
60 kg/ha N foliar urea	Nil N	anthesis
no extra N applied	GAI 3	-
60 kg /ha N foliar urea	GAI 3	anthesis
no extra N applied	GAI 5	-
60 kg/ha N foliar urea	GAI 5	anthesis
no extra N applied	Conventional N	-
60 kg/ha N foliar urea	Conventional N	anthesis
30 kg/ha N foliar urea on 20 June 1995	GAI 5	anthesis
30 kg/ha N foliar urea on 8 June 1995	GAI 5	anthesis
30 kg/ha N foliar urea + spreader	GAI 5	anthesis
30 kg/ha N foliar urea + sticker	GAI 5	anthesis

The last four listed treatments were made to duplicate those implemented at IACR-Rothamsted in 1995.

Growth analysis

A quadrat of 0.72 m^2 was placed in the plot and the crop removed by cutting the shoots just above soil level. Two sub-samples of roughly 10 % of the whole were taken, one for shoot number and GAI determination and the other for total N analysis. Samples were taken on two occasions, the first on 18 May 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

Stratified canopy measurement of urea deposition

The sample method was the same as that used at IACR-Rothamsted in 1995. Leaves were cut off directly into the bottle containing 200 ml 0.1 % triton X-100, the stem was cut in half and the ear was included with the top half of the stem for washing purposes but the area of the ear was determined separately. Complete stratified samples were taken immediately after urea had been applied and at the end of the sample period 96 hours later. At 12, 24 , 36, 48 and 72 hours after urea application ten flag leaves were removed from each plot and washed. Only the complete stratified samples taken at 0 and 96 hours were analysed for total N content.

Hand harvest - yield components

A 0.72 m^2 area of crop was harvested by cutting the shoots off above soil level. The ears were removed, counted and weighed and then threshed using a stationary threshing machine and the fresh weights of grain and chaff were recorded. An approximate 10 % sub-sample of straw was taken for determination of dry weight. The grain sample was cleaned to remove split grains, rachis and chaff and then the number of grains in the sample was counted. The yield of grain, straw and chaff (t/ha) and the total fresh and dry weight (g/m^2) were determined.

Combine harvest

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

Measurement of urea present on the crop surface

Quantifying the amount of urea present on the surface of the crop was found to be difficult. A number of different methods were available for use and several were tested extensively. The three main methods were i) the removal of urea from the surface of the plant material by washing in water or another liquid, ii) measuring the change in the tissue N content of the plant material after the application of foliar urea had occurred and iii) the use of N^{15} labelled urea.

From the literature, the most commonly used method to remove urea was washing the plant material in distilled water (Cook and Boynton, 1952; Klein and Weinbaum, 1985). A surfactant was found to improve the recovery of urea to 90% (Klein and Zilkah, 1986). Measuring the change in tissue N content was found to be more variable but had been used by a number of authors to support results obtained from washing techniques (Wesley, Shearman and Kinbacker 1985).

N^{15} labelled foliar urea had been used extensively on many plant species including soybeans (Morris and Weaver 1983) and sugar beet (Beringer and Koch 1985). Bowman and Paul (1989, 1990) tested leaf washing, tissue N analysis and N^{15} on tall fescue (*Festuca arundinacea*) and creeping bent grass turf (*Agrostis stolonifera* L.). 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.

Initial testing of methods for measurement of urea

Leaf washing techniques

The third method to be tested was eventually selected for general use. The approach was to remove urea from the leaf surface by washing and analyze the urea present in solution by direct colorimetric determination.

A range of different solutions was tested, including 1:1 ethanol or methanol with water, (Holloway personal communication), and the agricultural adjuvants Vassgro Spreader (Vass) and Citowett (BASF), both non-ionic wetters. All were found to interfere with the subsequent analysis of urea.. However, a 0.1 % solution of triton X-100 (Sigma), another non-ionic wetter proved to be compatible with the method used for analysis of urea.

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 ten organs or from individual leaves and the urea was easily detected in 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 found to be sufficient for the removal of the urea from the leaf surface, after the plant material was removed using forceps, the washing solutions were immediately frozen at -20 °C to prevent any enzymic or bacterial degradation.

Direct determination of urea in solution

The direct determination of urea in solution was selected because it did not involve the difficult and uncertain process of enzymatic conversion of urea.
The amount of urea present in solution was determined directly using the colorimetric method of diacetyl monoxime (DAM). Diacetyl monoxime (2,3-butanedione oxime) reacts directly with thiosemicarbazide (TSC) and urea under acidic conditions. The dynamics of the reaction are not known; however, it is thought that urea may react with DAM to form pyrimidine or triazine derivatives. No explanation for the action of TSC in the assay has been found (Bremner 1982).

The method has been consistently used by many 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 here was adapted from that of Mulvaney and Bremner (1979), modified from Douglas and Bremner (1970). 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. Three standard solutions of known urea concentration and a blank of 0.1 % triton X-100, were included in each set of samples analyzed, to provide a calibration graph for calculation of the amount of urea present in solution.

Reagents

1. DAM reagent : 2.500 g diacetyl monoxime (Fluka) dissolved in 100 ml of demineralized water.
2. TSC reagent : 0.250 g thiosemicarbazide (Fluka) dissolved in 100 ml of demineralized water.
3. 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.
4. 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.

5. 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
6. 100, 200 and 400 mM urea solutions : 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 per week.

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. They 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 mixed gently.
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, it was diluted of 1:10 in 0.1% triton X-100 and re-analyzed as above. All solutions were analyzed in duplicate.

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 employed a modified version of the Dumas digestion method. The process involved the combustion of the plant material at 1250 °C in pure oxygen producing N_2 and NO_x gases. These gases were then passed through two tubes containing an anhydrous material to remove any water vapour present and then the No_x were reduced to N_2 in the presence of a catalyst. Carbon dioxide and any remaining water vapour were then removed and the N_2 gas, in a helium carrier gas was passed over a conductivity cell which measured the amount of N present. A percentage value for the N content of the material was then produced.

Controlled environment experiments

At IACR Rothamsted, additional experiments were carried out under controlled conditions in order to try to examine in more detail the factors that may have affected the uptake of foliar applied urea in the field.

N^{15} experiment

An experiment involving N^{15} was carried out with a two-fold purpose. i) the first was to obtain a balance of N, accounting for the N present in the system, such that if the amount that had been applied to the leaf was known and the amount that was present in the plant material, the difference between the two values would be the amount lost through volatilization. ii) to examine the fate of foliar urea after uptake by the leaf, determining whether the urea was transported directly to the ear or whether it remained either in the flag leaf or in other leaves and the stem.

During anthesis, N^{15} labelled urea was applied to the flag leaves of plants grown in a glasshouse. The dynamics of loss of urea from the upper surface of the flag leaves was examined over a 96 hour period.

Experiment design

There were three replicates of nine separate samples-times during the 96 hours of the experiment. Three plants per replicate were used for analysis on each sample occasion. After application of urea (see below), the leaf and the stem material was bulked but the ear and the flag leaf were treated separately. A prespray sample was taken to determine the background levels of N^{15} in the plant, and on this occasion and at the end of the experiment, at 96 hours, the roots and the perlite/terra green growth medium were also sampled to check whether N from foliar urea could be translocated to the roots and then excreted into the growth medium (Poulton,P.R., personal communication).

Application method

The application of urea was made by a small hand operated plant mister. The nozzle was set so that a relatively fine spray was produced and every squeeze of the spraying mechanism delivered 0.75 ml of solution, measured by weight.

A sheet of perspex was held at each corner by four retort stands and set at the height of insertion of the ligule of the flag leaves on the stem of the plants to be sprayed. A sheet of filter paper (Whatman No. 1) 42 cm x 59.4 cm in size was weighed and then laid over the sheet of perspex and secured in position using pieces of electrical tape of known weight. Three plants were then placed adjacent to the perspex sheet and their flag leaves laid out across it and secured to the filter paper at the tip of the leaf using a piece of tape of known weight. A second sheet of filter paper of known weight was then held in front of the stems and ears of the plants. N^{15} labelled urea was applied using the hand operated mister by directing the output from the nozzle at each leaf in turn, so that three 0.75 ml deliveries of spray were made over the three flag leaves. The weight of the mister was measured before and after application. The leaves were then allowed to dry for approximately one minute before the tape holding the leaf down was carefully removed using scissors and forceps. The leaf was not allowed to spring up and the plants were removed taking care not to knock or touch the sprayed leaves. The filter paper held in front of the stems and ears was reweighed and the total weight of the tape and filter paper attached to the perspex sheet was also measured.

In each replicate one sample was taken directly after the urea had been applied and in this case the tape on the leaf was removed and the leaves cut off just above the ligule and they were then placed in 200 ml of 0.1% triton X-100 solution for ten minutes. Groups of three flag leaves per replicate were sampled at 4, 8, 12, 24, 48, 72 and 96 hours after application. The leaves were cut off just above the ligule, held using a pair of tweezers and then placed in 200 ml of 0.1 % triton X-100 for ten minutes. A 10 ml sample of the solution was taken and frozen separately and the rest of the washing solution was also frozen. The area of all the flag leaves, ears, other leaves and the 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 10 ml samples of the washing solutions was determined using the diacetyl monoxime assay for urea. The rest of the samples were retained for distillation and analysis of the N^{15} present in solution, if necessary.

Analysis

The plant samples were ground to a very fine flour using a Teamer mill. 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

Calculations

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

$$F = T * ((p-q)/f)$$

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:

$$T = M(n/100)$$

where:

M = total dry weight of the plant material

n = % N in plant material

and the percentage recovery of labelled N in crop is

$$F / Q *100$$

where :

Q = mass of labelled N applied.

T, F and Q are all expressed as mg.

3. Grain Quality analyses

Samples of grain were taken from crops receiving conventional N and N according to Canopy Management in the field tests of Canopy Management. Funding was sufficient for 24 samples to be analysed per year and samples were selected following consideration of grain yields and on the basis of laboratory analyses of Hagberg Falling Number (HFN), specific weight (Sp. wt.), protein content and 1000 grain weight (TSW) performed on wheat samples at ADAS Wolverhampton.

Milling and Baking tests were conducted according to standard procedures (Anon, 1992). Zeleny sedimentation and Chopin Alveograph tests were carried out according to the relevant ICC Standard Methods (ICC:1972, 1992 and 1994). The quality tests used to assess wheat for milling, export and breadmaking (plus any abbreviations and appropriate test units were as follows):

Milling quality

Screenings (Screen.), %

Flour yield, %

Air jet sieve analysis, % > 75microns

Starch damage, Farrand units

Grade Colour, GCF units

Export quality

Chopin Alveograph

W value, Joule . 10^{-4}

P/L ratio

Zeleny sedimentation volume, ml

Breadmaking quality

Wheat SDS sedimentation volume, ml

Flour protein content(F.Protein), % at 14% moisture

Falling Number (F.No.),s

Water absorption (Water Ab.), % based on Farinograph 600line

Chorleywood bread Process

loaf volume (CBP volume), ml

& crumb score (CBP crumb score)

Spiral mix baking process

loaf volume (SP volume), ml

Gel protein

weight, g/5g

Rheology, elastic modulus G'

An explanation of these procedures is given below. FTP methods are described in detail elsewhere (Anon, 1991).

Milling quality

Milling (Flour yield, %)

Wheat samples were cleaned using a Carter-Day Dockage tester before conditioning to 16.0% moisture for breadmaking varieties and 15.0% for soft, biscuit making wheat varieties. Samples were milled using FMBRA method MS 0001 to provide white flour for quality testing and to measure flour yield or extraction. Mill settings were optimised in order to achieve flour yields and starch damage levels as close as possible to current commercial practice for a CBP bread flour.

Grain texture(%)

Varietal hardness was assessed by air-jet sieve analysis of the milled flour, using a 75 micron sieve, according to FMBRA Method MS 0007. The percentage of material which passes through the sieve is measured, soft wheat varieties producing values above 50% whilst hard wheats produce values below 50%.

Flour colour (GCF)

Flour colour grade was measured using the Kent-Jones and Martin Colour Grader, series 4 (FTP Method 0007/4). The reflection of light at 530nm from a flour/water paste contained in a glass cell was measured. This provides a measure of the bran contamination in a white flour sample, which is related to milling quality. High values tend to indicate greater bran contamination and can be expected to have a detrimental effect on breadmaking quality.

Starch damage (Farrand units, FU)

Starch damage was determined according to FTP method 0005. The level of starch damage produced on milling is an important milling quality parameter. The miller aims to control starch damage during milling in order to control water absorption and optimise flour quality for breadmaking.

Baking quality

Wheat SDS sedimentation volume(ml)

The SDS sedimentation volume was measured following FTP method 0010. This uses a KT-ground wholemeal and provides an indication of breadmaking potential of a wheat sample. Breadmaking varieties should have SDS Sedimentation volumes above 55ml. The SDS volume is primarily a measure of protein quantity but is affected by changes in protein content. Exceptionally high SDS volumes, above 80ml, do not indicate that the variety will produce superior quality bread.

Flour protein(% at 14% moisture content)

Flour protein and moisture contents were measured by NIR according to FTP method 0014. Flour protein content was then corrected to a 14% moisture content basis.

Falling Number(s)

Flour Falling Number was measured according to FTP method 0006, the weight of flour used being adjusted according to the moisture content of the flour. This test provides an estimate of the alpha-amylase activity of the flour and this figure is then used to calculate the amount of fungal alpha-amylase required in test baking.

Farinograph water absorption (%)

The water absorbing capacity of the flour samples was measured using the Brabender Farinograph working to the 600 BU line (FTP Method 0004). This test provides a measure of the water required to mix a dough to a fixed consistency which is used subsequently in test baking.

*Test baking**

(i) Chorleywood Bread Process (CBP loaf volume and crumb score)

A standard laboratory-scale Chorleywood Bread Process (Method 1AA) was used to produce 400g white loaves. In this high speed mixing test bake, doughs are mixed to a fixed work input level of 11 watt hours/kg. Details of the method used are given below. Each sample is mixed and baked in duplicate. For each replicate bake, loaf volume was measured by seed displacement and a score (maximum 10) is allocated for crumb cell structure. A high score for crumb cell structure is awarded for a close and uniform structure of small, thin-walled cells. A photographic record of the internal structure of all CBP bread produced is retained for reference. Details of this process are given below:

Bread type: 400g, white, Mixing machine: Morton

Control recipe:	**% of flour weight**	**g/mix**
Flour	100	840
Yeast (compressed)	2.5	21
Salt	2.0	16.8
Fat (Ambrex, slip point c.45^{O}C)	1.0	8.4
Ascorbic acid (100ppm AA)	0.01	0.084
Water	As determined by Farinograph using 600 line	

The *alpha*-amylase activity of the flour is adjusted to 40 FU by the addition of fungal *alpha*-amylase. Flour `base' level of *alpha*-amylase is estimated from the Falling Number.

Dough processing:

Mixing machine	:	Two speed Morton
Beater speed	:	30 sec slow rest fast
Work input	:	11Wh/kg
Pressure	:	Atmospheric
Dough temperature	:	30.5 ± 1^{O}C
Scaling	:	By hand to 454g
First moulding	:	Mono 6" bench moulder (R7mm, P41mm)
First proof	:	10 min at 27^{O}C
Final moulding	:	Mono bench moulder (R7mm, P41mm)
Pan size	:	160mm x 98 mm, 83mm deep
Shape	:	Unlidded

Proving conditions	:	43^{O}C, humidity to prevent skinning
Proving height	:	10 cm (max time 60 min)
Baking temperature	:	244^{O}C
Oven type	:	Simon electric reel
Baking time	:	25 min
Baking humidity	:	Water for steam
Cooling	:	Open rack at ambient
Storage	:	Cupboard at ambient

(ii) Spiral (loaf volume)

A standard Spiral mix test baking procedure was also used in this study. This system uses slower speed mixing and mixes for a longer but fixed amount of time (8 minutes) to develop the dough.

Details of the method are given below. Each sample is tested singly by this baking procedure. Loaf volume is measured as before. This baking system produces a much more open crumb structure, a photographic record is kept, but no score is assigned to this feature.

Bread type: 400g, white, Mixing machine: Spiral, Spi 10

Control recipe:	**% of flour weight**	**g/mix**
Flour	100	1400
Yeast (compressed)	2.5	35
Salt	2.0	28
Fat (Ambrex, slip point c.45^{O}C)	1.0	14
Ascorbic acid (100ppm AA)	0.1	0.14

Water As determined by Farinograph using 600 line

The *alpha*-amylase activity of the flour is adjusted to 40 FU by the addition of fungal *alpha*-amylase. Flour `base' level of *alpha*-amylase is estimated from the Falling Number.

Dough processing:

Mixing machine	:	Two speed spiral
Beater speed rev/m	:	99 slow 197 fast
Mixing time min	:	2 slow, 6 fast
Pressure	:	Atmospheric
Dough temperature	:	30.55 ± 1^{O}C
Scaling	:	By hand to 454g
First moulding	:	Mono 5" bench moulder (R8mm, P43mm)
First proof	:	10 min at ambient temperature
Final moulding	:	Sorenson commercial (R7, W5.5, P1.25)
Pan size	:	160mm x 98mm, 83mm deep
Shape	:	Unlidded
Providing conditions	:	43^{O}C, humidity to prevent skinning
Proving height	:	10 cm (max time 60 min)
Baking temperature	:	260^{O}C
Oven type	:	Direct gas-fired Reel (6 tray)
Baking time	:	25 min
Baking humidity	:	No steam injected
Cooling	:	Open rack at room temperature
Storage	:	Closed cupboard overnight at 21^{O}C

*Gel protein quantity(g/5g flour) and quality (G^1)**

10g flour was defatted with 25ml petroleum ether (b.p. 40-60^{o}C) for 1 hour, filtered and dried. 5g of defatted flour was stirred with 90ml of 1.5% sodium dodecyl sulphate for 10min at 10^{o}C then centrifuged at 25000rpm for 40min. The gel protein layer was removed and weighed.

The weight of gel protein represents the amount of functional protein present in the flour. It consists, principally, of glutenin and is genetically controlled. In general, breadmaking wheats have higher levels than do feed or biscuit-making varieties. A typical range for breadmaking would be 9-12g/5g of flour (wet-weight basis).

The quantity of gel protein does not always reflect the baking quality of a flour. Two recent examples; Fresco and Pastiche had levels appropriate for breadmaking but Fresco was too strong and Pastiche too weak for optimum performance in the CBP. The elastic modulus(G^1) of gel protein can distinguish between these quality variations. The optimum range varies from site to site and from season to season, but in recent studies it has been shown that samples with G^1 of less than 15Pa and those greater than 40Pa may not give optimum performance in the CBP.

The quality of the prepared gel protein was assessed by measurement of the elastic modulus (G^1) using a Bohlin rheometer.

Quality for Export

Zeleny sedimentation volume(ml)

Samples of wheat(150g) were conditioned to 15.0+/-0.5% moisture content before being milled to produce a white "break" flour on a Brabender Sedimat mill according to ICC standard No 118. This mill produces a flour of around 12-15% extraction. Zeleny sedimentation volumes were performed according to ICC standard No 116. In this test the flour is suspended in alcohol and lactic acid. Under these conditions the glutenin proteins swell and the volume occupied by the flour suspension after settling provides a measure of breadmaking potential. Breadmaking varieties will normally produce Zeleny values in excess of 30ml. The test is a measure of protein quality but is also affected by protein content ie increasing protein content should produce higher Zeleny values.

Chopin Alveograph

Samples of flour were mixed to produce doughs using a constant amount of 2.5% salt solution. The dough was extruded, sheeted and cut into discs. The discs were incubated at constant temperature for 20 minutes before Alveograph testing. Each disc of dough was inflated to produce a bubble which increases uniformly in volume until it bursts. A pressure-time curve is produced during expansion and certain values are recorded as follows:

P is the maximum pressure achieved during the test and is related to the Resistance of the dough to stretching.

L	is the length of the alveogram to the point of rupture. This provides a measure of the extensibility of the dough.

P:L	called the configuration ratio. For bread wheats a value of 0.5-0.8 is often considered desirable.

W	is the area under the curve and is proportional to the energy required to inflate the bubble to bursting point. this figure provides an indication of gluten strength and a bread wheat would be expected to produce a value in excess of 140.

Results

This section presents the main results of the experimental work conducted during this investigation of the potential for the use of Canopy Management to determine fertiliser N amounts and timings for winter wheat. The format will be an examination of the individual components of the theoretical framework proposed in the Introduction to this report which identified a series of quantitative links between application of fertiliser N and the formation of yield and quality. Most of the data presented come from the field tests of Canopy Management (mostly from the University of Nottingham and ADAS Boxworth where studies where made in detail, but where necessary, including the most relevant results from other sites). Data from the studies at AICR Rothamsted and CCFRA are included where appropriate.

N uptake - soil mineral N

Soil mineral N - magnitude and location of residues

The aim of this experimental programme was to compare fertiliser N use according to Canopy Management with conventional N use over a wide range of crop conditions and soil N residues (background crops). Soil mineral N measured in February does not adequately reflect the full impact of previous fertiliser N use because it does not account for crop N uptake at that time. Therefore, in Table 14, Table 15 and Table 16, the amount of soil mineral N in the top 90cm of soil and crop N uptake in February are presented and the sum of soil and crop N is the estimated 'soil N supply' resulting from previous fertiliser N use. A key part of the test of Canopy Management was to examine whether this estimated soil N supply can be a good prediction of measured crop N uptake.

Table 14 The amount of soil mineral N (0-90cm), crop N and estimated soil N supply in the Canopy Management test crops in February 1993.

Site and background crop		*SMN (0-90) kg/ha N*	*Crop N uptake kg/ha N*	*'Total soil N supply'*
University of Nottingham				
	HNES	78	8	86
	HNLS	99	1	100
	LNES	62	8	70
	LNLS	76	1	77
ADAS Boxworth				
	HNES	102	26	128
	HNLS	135	3	138
	LNES	85	23	108
	LNLS	102	3	105
ADAS Terrington				
	HNES	71	5	76
	HNLS	76	0	76
	LNES	77	5	82
	LNLS	70	0	70
ADAS Rosemaund				
	HNES	86	5	91
	LNES	62	5	67

A satisfactorily wide range of soil N residues was achieved in February of each year. In 1993, application of a difference of 200kg/ha N to the preceding crop increased the amount of soil N beneath both early and late sowings at all sites except at ADAS Terrington where there was no significant difference between any of the background crops. The largest difference between high and low residues 24 kg/ha N at ADAS Rosemaund. Generally in this year, N uptake in February was small, less than 10 kg/ha except for early sowings at ADAS Boxworth where about 25 kg/ha was taken up overwinter. Adding soil and crop N together, total soil N supply varied twofold from 67 to 138 kg/ha.

Table 15 The amount of soil mineral N (0-90cm), crop N and estimated soil N supply in the Canopy Management test crops in February 1994

Site and background crop	*SMN (0-90) kg/ha N*	*Crop N uptake*	*'Total soil N supply'*

		kg/ha N	
University of Nottingham			
HNES	104	3	107
HNLS	113	0	113
LNES	88	2	90
LNLS	85	0	85
ADAS Boxworth			
HNES	93	4	97
HNLS	98	1	99
LNES	63	5	68
LNLS	79	1	80
ADAS Terrington			
HNES	67	6	73
LNES	59	7	66
ADAS Rosemaund			
HNES	138	3	141
LNES	115	3	118
Harper Adams Agricultural College			
LNES	59	8	67
LNLS	60	2	62
Arable Research Centres Cirencester			
LNES	92	5	97
LNLS	85	2	87

In 1994, differences in soil N were slightly larger, ranging from 59 kg/ha under the LNES background crop at ADAS Terrington to 138 kg/ha under the HNES crop at ADAS Rosemaund. Again, little difference was found between soil residues at ADAS Terrington. The largest difference between residues was 30 kg/ha N at ADAS Boxworth under early sowings. Crop N uptake in February was again small; less than 10 kg/ha at all sites. Thus total N supply largely reflected the magnitude of the soil N residue.

Table 16 The amount of soil mineral N (0-90cm), crop N and estimated soil N supply in the Canopy Management test crops in February 1995

Site and background crop	*SMN (0-90) kg/ha N*	*Crop N uptake kg/ha N*	*'Total soil N supply'*
University of Nottingham			
HNES	40	76	116

	HNLS	46	29	75
	LNES	14	34	48
	LNLS	28	23	51
ADAS Boxworth				
	HNES	48	32	80
	HNLS	80	4	84
	LNES	22	29	51
	LNLS	56	4	60
ADAS Terrington				
	HNES	123	54	177
	HNLS	125	15	140
	LNES	17	40	57
	LNLS	30	13	43
ADAS Rosemaund				
	HNES	78	40	118
	LNES	42	29	71
Harper Adams Agricultural College				
	LNES	17	11	28
	LNLS	15	5	20
Arable Research Centres Cirencester				
	LNES	38	4	42
	LNLS	34	1	35
ADAS High Mowthorpe				
	HNES	45	17	62
	LNES	33	19	52
SAC Edinburgh				
	LNES	37	1	38
	LNLS	41	1	42

The relatively small differential in soil and crop N in February, following a difference of 200kg/ha N applied to the preceding crop (on average, 24 and 30 kg/ha in 1993 and 1994 respectively) encouraged the differential to be increased to 300 kg/ha for the set up crops for the final year of experiments. In contrast with the two previous years, the largest difference in soil N was at ADAS Terrington where 50 kg/ha N applied to the preceding crop resulted in smaller residues than either of the two previous years but, increasing fertiliser N to 350 kg/ha increased soil N to over 120 kg/ha. The difference in N residues was small at ADAS High Mowthorpe where the soil is shallow and stony with increased risk of leaching. At Harper Adams Agricultural College on the sandy clay loam, soil N was very low; less than 20 kg/ha. In 1995, crop N uptake over winter was larger than in the previous years particularly where N residues were large. In early sowings, crop uptake by February varied from 1 kg/ha at SAC Edinburgh where there was very little growth over winter to 76 kg/ha at the high N residue at the University of Nottingham. In this year, total soil N supply varied ninefold from 20 kg/ha at Harper Adams Agricultural College to 177 kg/ha at ADAS Terrington. This emphasises the potentially large variation in soil N available to crops in commercial production systems similar to those grown here.

The overall effect of increased fertiliser application to the preceding crop is shown for the sites used in all three years in Table 17. The effect on soil N plus crop N was generally similar (25 to 32 kg/ha N) except at ADAS Terrington where the average difference of 44 kg/ha resulted solely from the large difference in 1995.

The larger residues found in 1995 probably resulted from the increased differential in fertiliser applied to the preceding crop; a greater proportion of an application of 300 - 350 kg/ha would be surplus to crop requirement and hence not be taken up than would remain from an application of 200 - 250 kg/ha which was applied in the first two years.

An important finding from these measurements was the evidence that late sowing did not reduce the amount of soil N available to the crop; although late sowing consistently reduced the amount of crop uptake in February, this was offset by a larger amount remaining in the soil which was not leached. The overall effect of sowing date on the balance of residues between crop and soil is shown for the sites used in all years in Table 18. Late sowing, on average, reduced crop N uptake by 19 and 12 kg/ha on high and low N residues receptively, but the difference in total soil supply was only 5 and 1 kg/ha respectively. It therefore appears that there was no significant loss of soil N on these N retentive soils following late sowing. This is unlikely to be the case on more sandy / light soils.

Table 17 The effect increasing N application by 200 kg/ha in 1993 and 1994 and by 300 kg/ha in 1995, on soil N, crop N and total N supply in February.

Site	*N Residue*	*SMN (0-90) kg/ha N*	*Crop N uptake kg/ha N*	*'Total soil N supply'*	*Difference kg/ha*
University of Nottingham					

	High	80	20	100	***30***
	Low	59	11	70	
ADAS Boxworth					
	High	93	12	104	***25***
	Low	68	11	79	
ADAS Terrington					
	High	92	16	108	***44***
	Low	51	13	64	
ADAS Rosemaund					
	High	101	16	117	***32***
	Low	73	12	85	

Means of sowing dates and seasons at the University of Nottingham, ADAS Boxworth and ADAS Terrington and means of seasons at ADAS Rosemaund.

Table 18 Effect of early and late sowing on the N balance between crop and soil

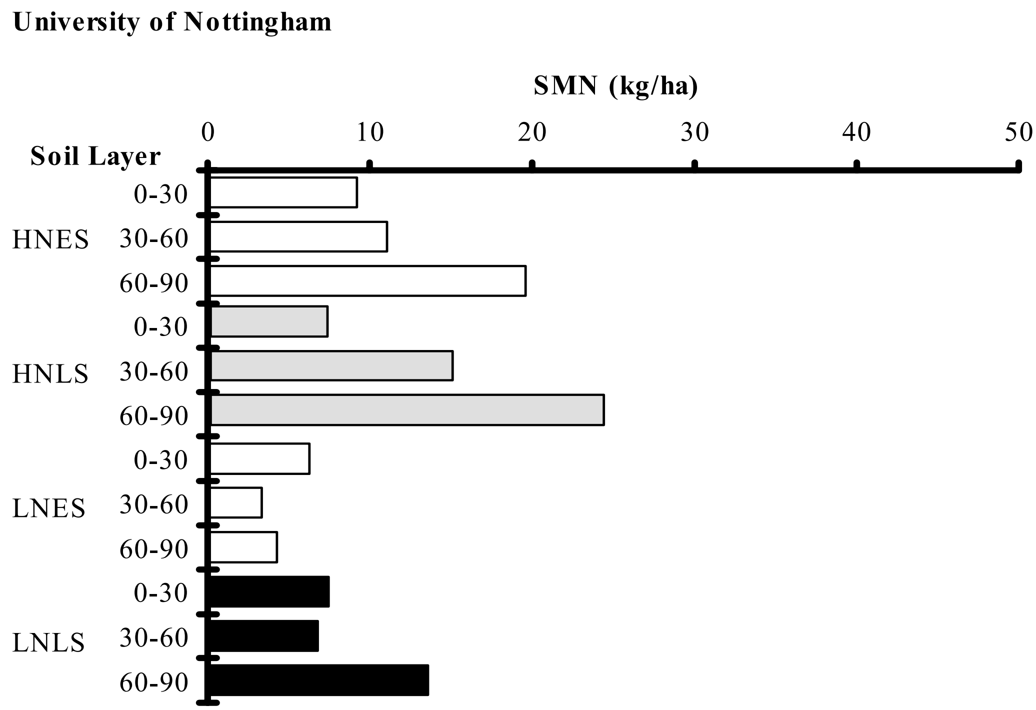
N Residue	*Sowing date*	*SMN (0-90) kg/ha N*	*Crop N uptake kg/ha N*	*'Total soil N supply'*
High	*Early*	82	26	108
	Late	97	7	103
Low	*Early*	54	18	72
	Late	66	6	71

Means of data from the University of Nottingham and ADAS Boxworth (where early and late sowing were made in each year: the late sowings at ADAS Terrington had to be abandoned and therefore the Terrington data could not be included in these averages.

In summary, applying more N to the proceeding crop consistently increased the amount of soil mineral N in February; average increases were between 20 and 40 kg/ha and were generally much larger than the change in crop N at this time. Although soil mineral N plus crop N was generally 30 kg/ha larger where more fertiliser had been applied, this was not consistent from year to year suggesting that it may be better to rely on accurate measurement of soil mineral N in spring rather than aim for prediction which might require comprehensive records / measurements (for example soil type, depth, rotation, previous N applications, applications of farm yard manure, crop uptake, likely mobilisation/ immobilisation and hydrologically effective rainfall) and may make prediction of soil N unreliable. Residual N can be considered as 'free' fertiliser N if N rates can be adjusted accordingly. It would appear from these data that there are likely to be numerous situations where soil mineral N under commercial crops is sufficiently large to allow fertiliser N rate to be reduced provided that soil mineral N in spring is a good measure of subsequent crop N uptake.

It is not only the amount of mineral N in the top 90cm of soil which will govern crop uptake, the location of N residues down the soil profile will influence the time of uptake which will be related to the degree of root penetration during winter / early spring. Also, there may be larger than expected leaching losses especially if soils are saturated and quantities of mineral N are deep in the subsoil and likely to be leached by subsequent rainfall before rooting will be sufficiently deep. The effect of location of soil N residues in the soil profile on crop uptake was examined for the crops grown at the University of Nottingham and ADAS Boxworth where crop N uptake was monitored fortnightly. The location of soil residues in the crops grown at the University of Nottingham and ADAS Boxworth are shown in Figure 4, Figure 5 and Figure 6.

In all situations, mineral N was distributed throughout the whole 90cm soil profile; over half was located below the topsoil (30cm). Following larger applications of N to the preceding crops, there was a tendency for the mineral N to be more uniformly distributed through the soil profile. For example, at ADAS Boxworth in 1994, almost an equal amount of residual N was in each of the three layers of soil. However, with less N applied to the proceeding crop, less mineral N was at depth (60 - 90cm). The presence of substantial amounts of soil mineral N below the top soil (> 30cm deep) found in these experiments provides valuable support for earlier observations that mineral N was often found beneath the topsoil particularly when large applications had been applied to the preceding crop. Presence of mineral N at depth will have implications for time of uptake which will be related to the progression of the root front and may also have bearing on N uptake later in the season when topsoils might be too dry for N to be taken up.



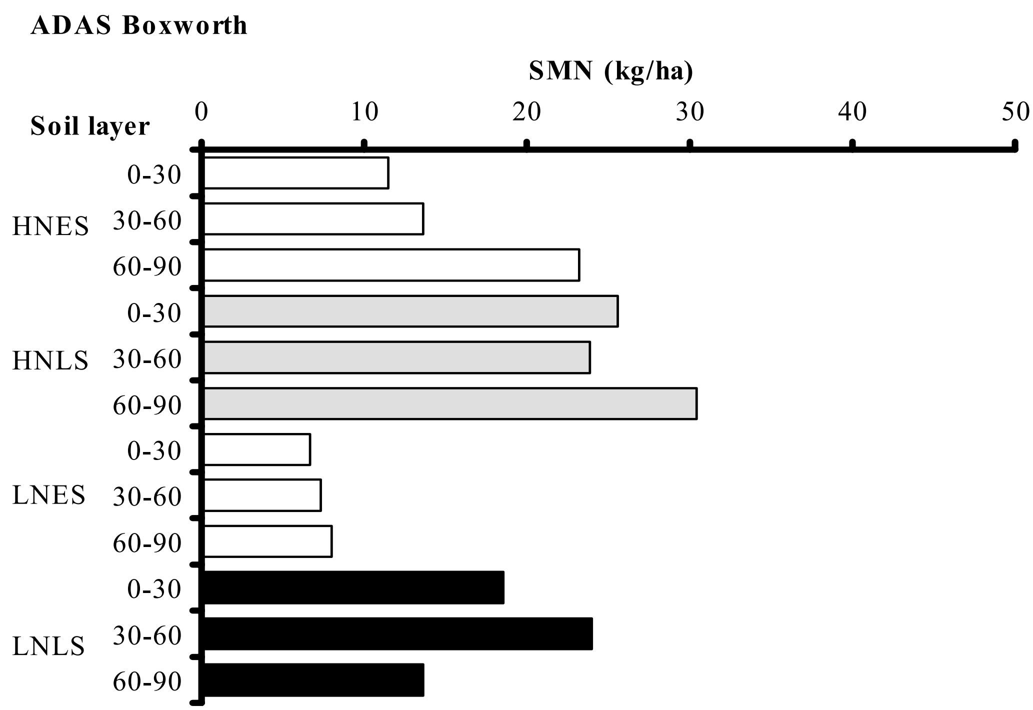
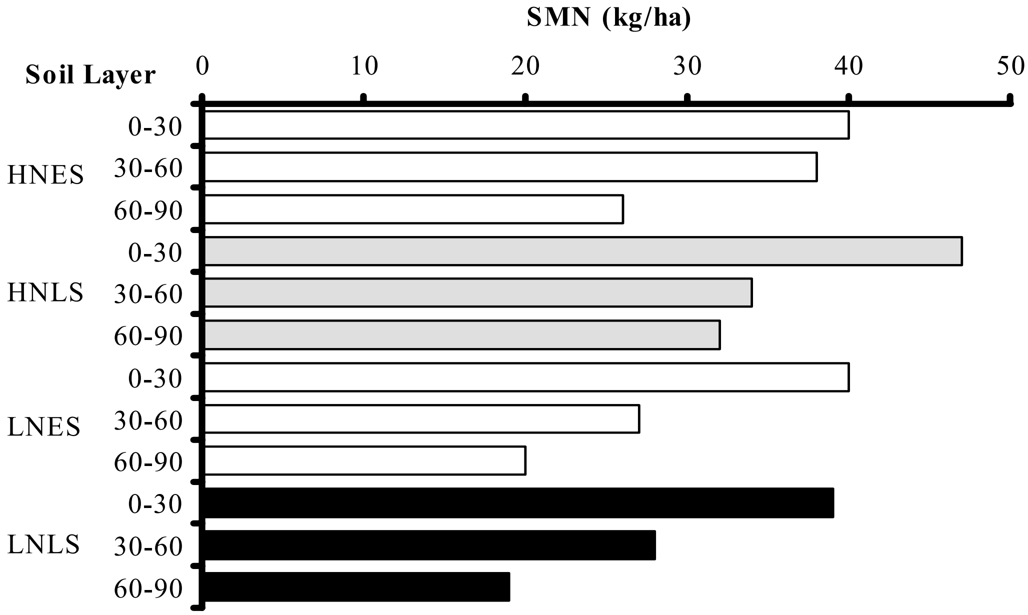


Figure 4 Location of soil mineral N (SMN) residues at the University of Nottingham and ADAS Boxworth in February 1993.

University of Nottingham



ADAS Boxworth

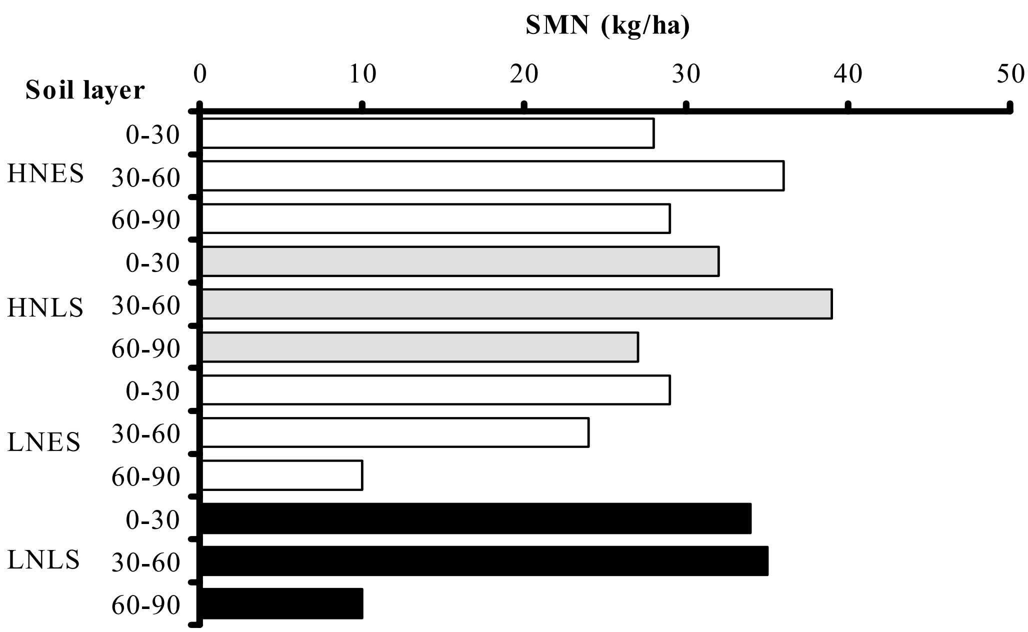
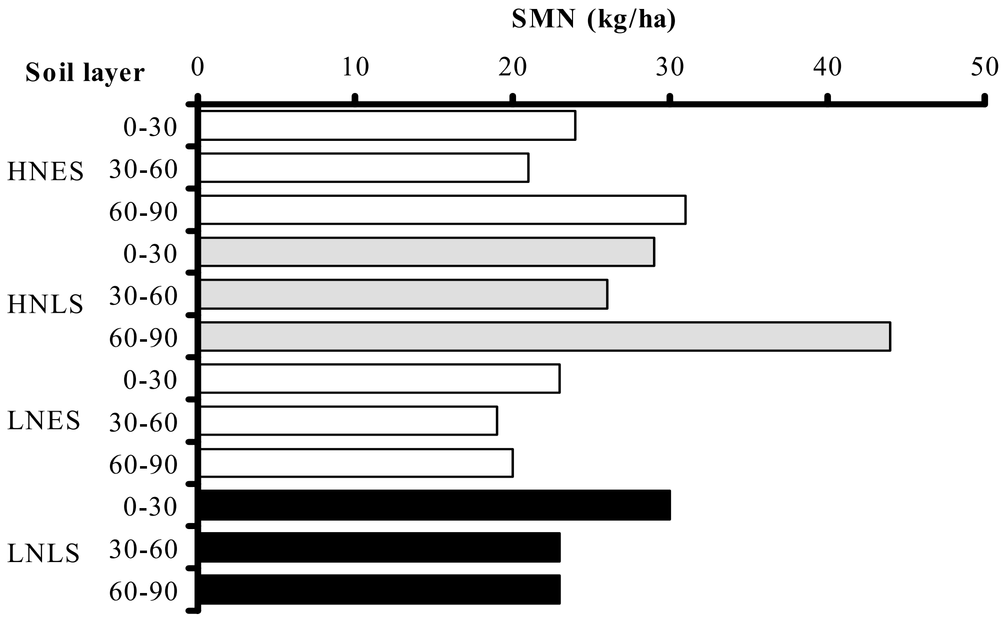


Figure 5 Location of soil N (SMN) residues at the University of Nottingham and ADAS Boxworth in February 1994.

University of Nottingham



ADAS Boxworth

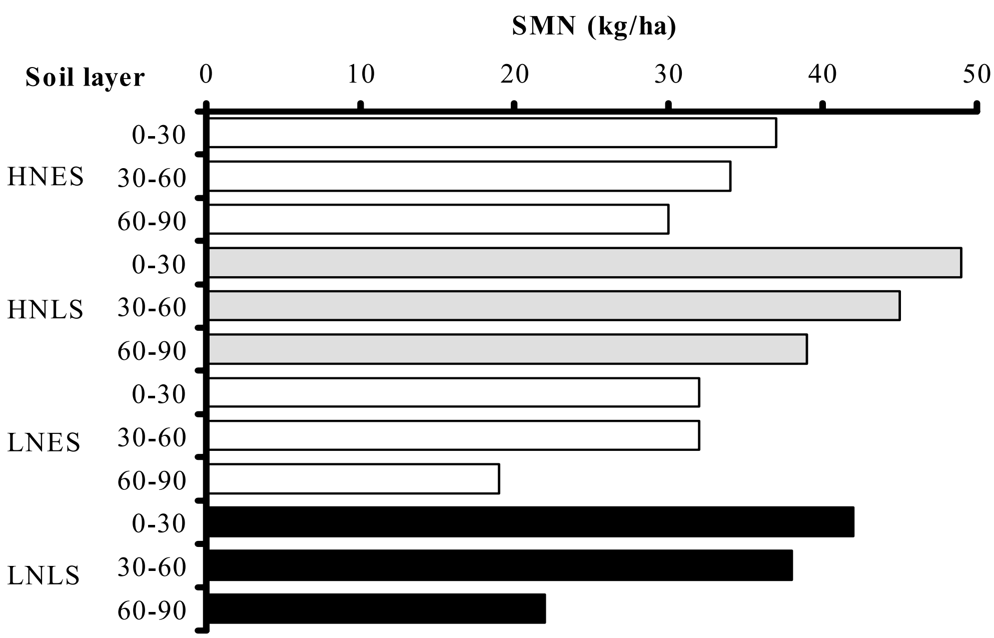


Figure 6 Location of soil N (SMN) residues at the University of Nottingham and ADAS Boxworth in February 1995

Soil mineral N - recovery at harvest

The aim of this work was to investigate whether or not the amount of soil mineral N measured in the top 90cm in February was a good indicator of subsequent crop uptake. This is a crucial step in the theoretical framework linking N uptake to yield formation because it may provide a measure of soil supply and therefore quantify the shortfall in N uptake required to meet the Canopy Management target canopy size.

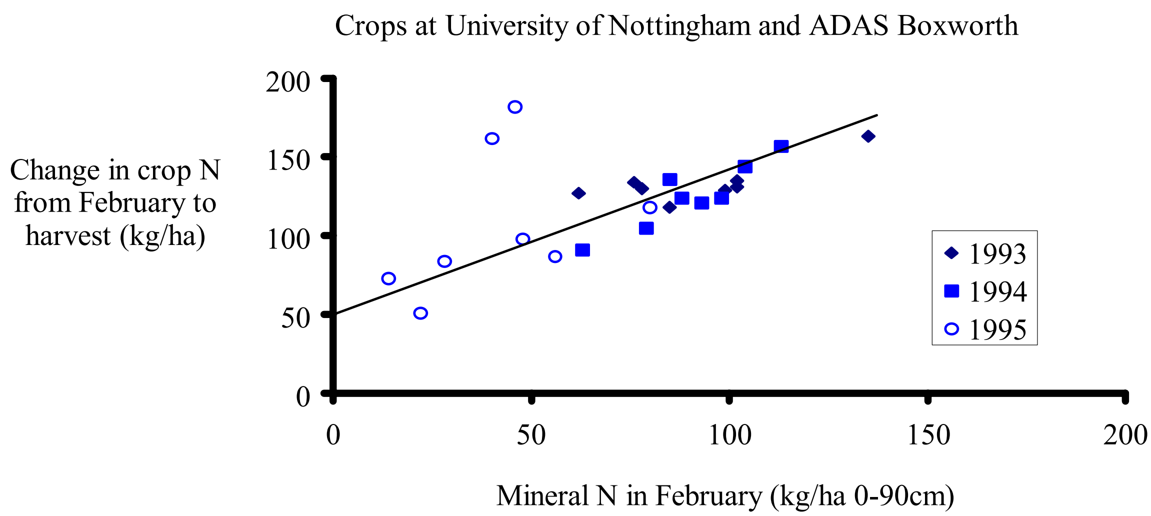
Recovery of soil mineral N was evaluated in the field tests of Canopy Management in crops which did not receive fertiliser N. For each of the comparisons between Canopy Management and conventional fertiliser N use, a wheat crop was grown following identical management but without fertiliser N. The relationship between soil mineral N in the top 90cm of soil in February and subsequent N uptake at harvest is shown in Figure 7.

The relationship between soil mineral N (0-90cm) in February and subsequent uptake was surprisingly direct, holding across three seasons. The relationship was tighter at higher levels of soil mineral N where variation is usually large and this was surprising. Soil mineral N accounted for 75% of the variation in crop N uptake between February and harvest showing clearly that the amount of soil mineral N measured in spring is the major determinant of crop N recovery by unfertilised crops and that unassociated variation in factors such as summer mineralisation, summer N losses and N deposition is relatively minor.

There were two outliers in the relationship. These were the early and late sowings at the high N residue at Sutton Bonington in 1995. In these two cases, the measurement of soil mineral in February underestimated crop recovery by harvest. The reason for this is unclear. It is unlikely that it was due to high levels of mineral N at below 90cm, perhaps from previous applications FYM, because the sowings at the low N residue, which had low levels of mineral N, showed correspondingly low uptakes at harvest. It may be that a significant proportion of the N residue from the preceding crop's fertiliser N was leached below 90cm and was then recovered in the following test of Canopy Management.

The relationship between soil mineral N in February and offtake by nil N crops at harvest varied slightly depending whether all crops were examined (y=1.07x +25) or the examination was restricted to only the crops grown at The University of Nottingham and ADAS Boxworth (y=0.82x + 53.5). This difference in the two relationships probably reflects the increased number of crops grown in 1995 where, in general, there was less mineral N in February and, the variability tended to be greater with smaller N residues. However, the outcome from the two equations is very similar. Across a range in soil mineral N from 50 to 200 kg/ha, the first equation predicts 100% recovery plus an amount which gradually increases with size of the soil N residue from 25kg/ha at 50 kg/ha soil N to about 35kg/ha at 200 kg/ha soil N whilst the second equation predicts 100% recover plus 45 kg/ha at 50 kg/ha soil N and 20 kg/ha at 200 kg/ha soil N. Thus, there is robust evidence showing that soil N is recovered with at least 100% efficiency plus, on average, an extra 30 kg/ha. The tight relationship between soil mineral N and subsequent uptake might infer that all the mineral is depleted however, it is unlikely that the same N that was measured in February would be the N that was recovered during crop growth; mineralisation-immobilisation turnover would have continued concurrently with crop N uptake. Nevertheless an amount equivalent to about 30kg/ha over 100% of the soil mineral N was recovered at harvest. Thus, there must have been a close balance between mineralisation and immobilisation. Furthermore, the significant intercepts in the relationships at 53 kg/ha (when determined for crops at the University of Nottingham and ADAS Boxworth only) or 23 kg/ha (when determined for all crops) signifies spring and summer uptake of N are not influenced by initial soil mineral N levels; this may possibly relate to N deposited in rain or dust during late spring and summer.

The strong link between soil mineral N and crop uptake at harvest is of considerable importance. It shows that for a wide range of crop conditions, recovery of soil N by unfertilised crops between February and harvest can be predicted with accuracy. Although there was still some variation in soil N recovery unaccounted for, it is important that measurement of soil mineral N never markedly overestimated soil N supply. This is important because if there are circumstances where soil mineral N does not predict crop uptake well, it is better that it be underestimated leading to an overuse of fertiliser N and minimise the risk of a penalty in yield.



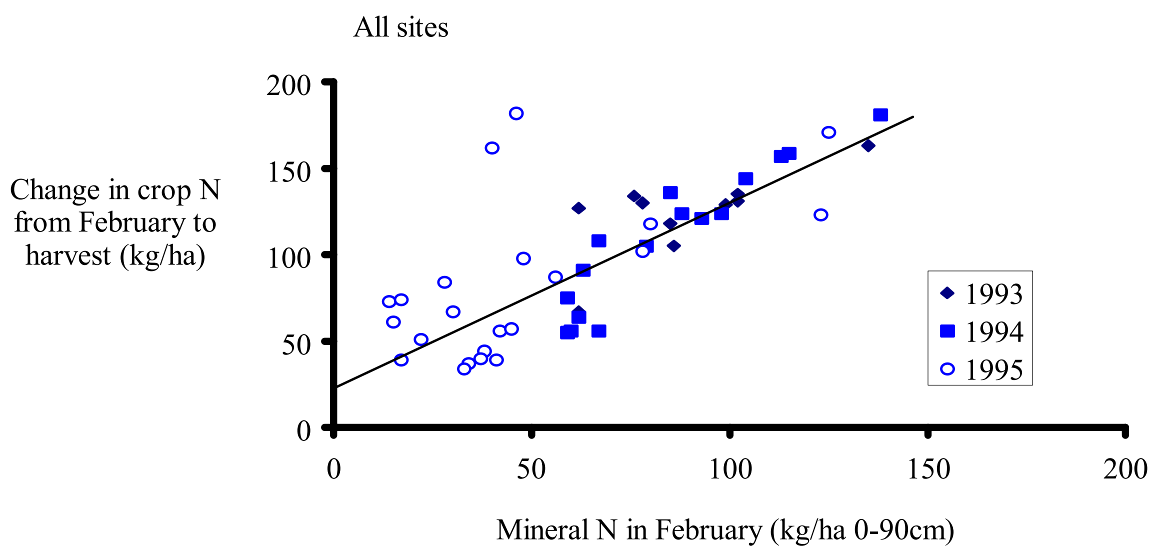


Figure 7 Relationship between soil mineral N in February and subsequent N uptake at harvest by crops not receiving fertiliser N for crops at the University of Nottingham and ADAS Boxworth and for all sites where Canopy Management was tested.

Soil mineral N - uptake through the season

The previous section has shown that recovery of soil mineral N by unfertilised crops can be predicted with confidence. However, to use this information as a basis for manipulating canopy size through Canopy Management, it is necessary to determine the period of crop growth during which the majority of uptake is likely to occur. Each year, N uptake was measured fortnightly in all the unfertilised crops at The University of Nottingham and ADAS Boxworth with the exception of the late sowing at ADAS Boxworth in 1995 which suffered very patchy establishment. There was a strong underlying pattern of N uptake shown by the average uptake at each site in each year. These data are presented as means of Sowing dates and N residues in Figure 8, Figure 9, Figure 10. Modification of this pattern through in sowing date and / or soil N residue was generally small hence, data are presented only where the major influences were found. For sowing date, this was at the University of Nottingham in 1994 where sowing was delayed by wet weather until early March and for N residue, this was at the University of Nottingham in 1995. These examples are shown in (Figure 11).

At both sites in all three years, the uptake of N by unfertilised crops was surprisingly constant during most of the season. The only cases where N uptake appears to have stopped before final harvest were at ADAS Boxworth in 1993 and 1994 (Figure 8, Figure 9). Previously it was thought that all N uptake occurred before flowering (Austin et al, 1980). This was clearly not the case. In all cases, uptake of N continued well past flowering into mid July. In half the cases, uptake continued through to harvest. The prevalence of N uptake after anthesis was surprising and challenges the hypothesis held at the start of this project that almost all N uptake was complete at anthesis. It indicates that the root and shoot system of wheat maintains the capacity to take up N until well after flowering. Approximately 75% of the N recovered at harvest was taken up by flowering and can be considered as N available for canopy expansion. The remaining 25% can be considered as N available for maintenance of the canopy or for maintaining protein deposition in grain.
There was some indication from these data that, where N uptake slowed or stopped before harvest, i.e. ADAS Boxworth in 1993 and both the University of Nottingham

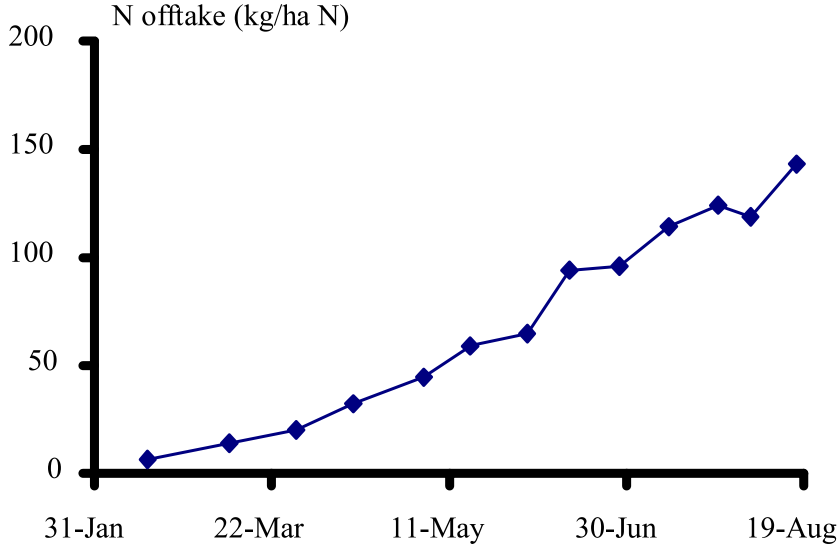
and ADAS Boxworth in 1994, it occurs where most of the mineral N was closer to the soil surface, i.e. less was at depth. This earlier cessation in N uptake may therefore reflect that all available N has been taken up or, that uptake has been curtailed because of dry conditions. Either way, the evidence here clearly shows that where there is soil mineral N at depth (30-90cm) there is potential for uptake throughout the whole of the season.

The effect of sowing date on uptake of N was most pronounced during early spring growth at the University of Nottingham where late sowing in early March restricted the onset of N uptake until late April (Figure 11). However, as the season progressed the disparity between early and late sowings decreased until there was no significant difference at harvest. The confirms earlier evidence from Webb *et al* (1995) who also demonstrated that large differences in sowing date from early autumn through to late spring had only small influence on recovery of soil N. This is important as it indicates that rooting depth in late sown crops is usually sufficient to recover mineral N down to 90cm.

Examination of the nil N crops at the University of Nottingham in 1995 clearly showed the dominant effect of N residue on N uptake (Figure 12). Whilst the link between soil mineral N measured in the top 90cm in February and subsequent crop N uptake was poor in this instance, presumably because most of the N residue was below 90cm, these data show that sowing date had no effect when residues were small but when large, late sowing reduced uptake through most of the season but by harvest there was no significant difference between sowings. This implies that later sown crops have less time for N uptake but can take up the available soil N at a faster rate.

Canopy Management relies upon quantifying the amount of soil mineral N that can be taken up by the time the canopy reaches maximum size. Examination of the link between the amount of soil mineral N in February and subsequent uptake before the canopy reached maximum size showed that the relation was best described by a straight line fitted through the origin because the measured intercept was not statistically significant. The resultant equation Y = 0.97X accounted for 70% of the variation in crop N uptake between February and maximum canopy size with 97% of the soil mineral N measured in February being recovered (Figure 12).

University of Nottingham



ADAS Boxworth

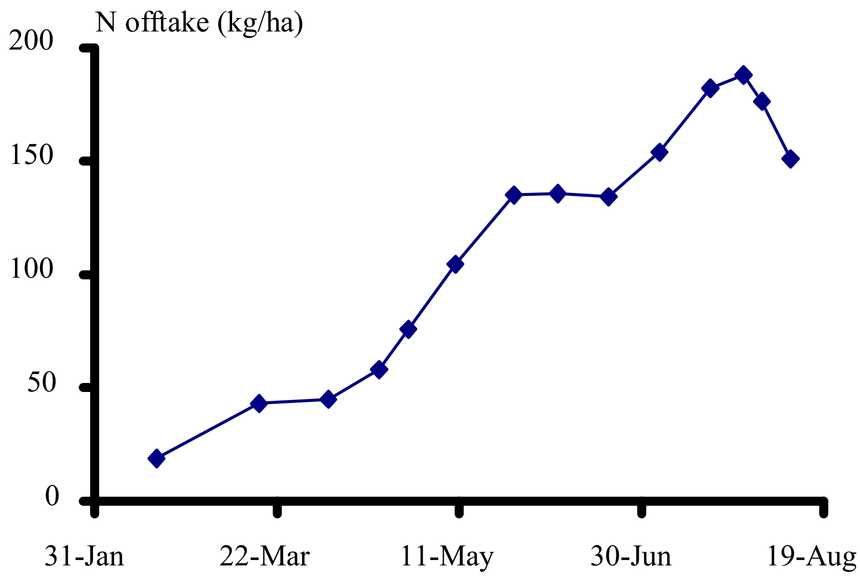
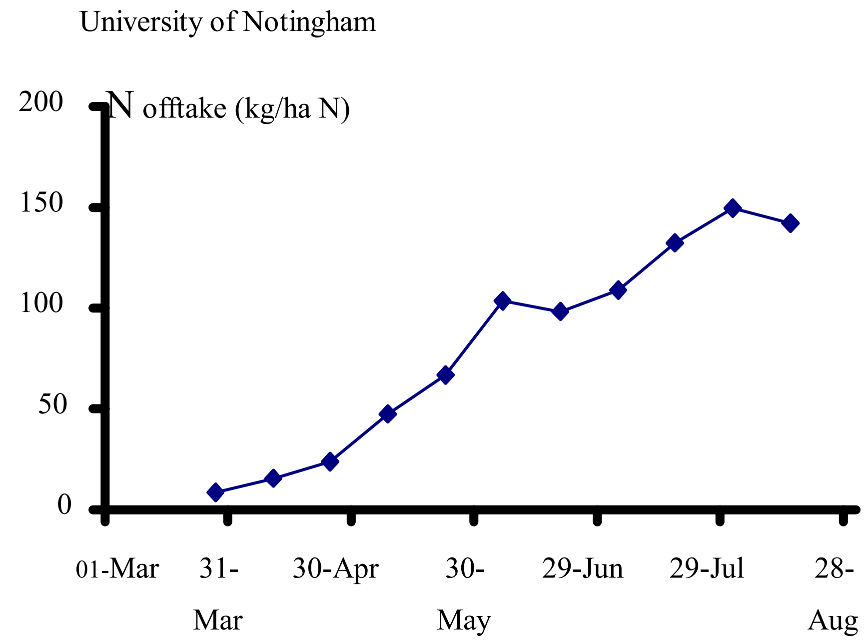


Figure 8 Uptake of N by unfertilised crops at the University of Nottingham and ADAS Boxworth in 1993. Data are means of sowing dates and N residues.



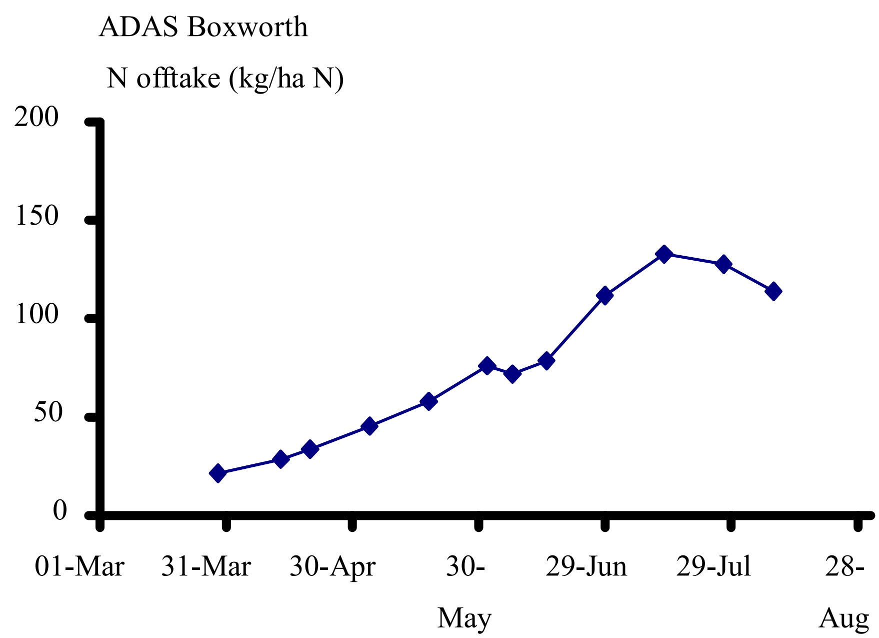
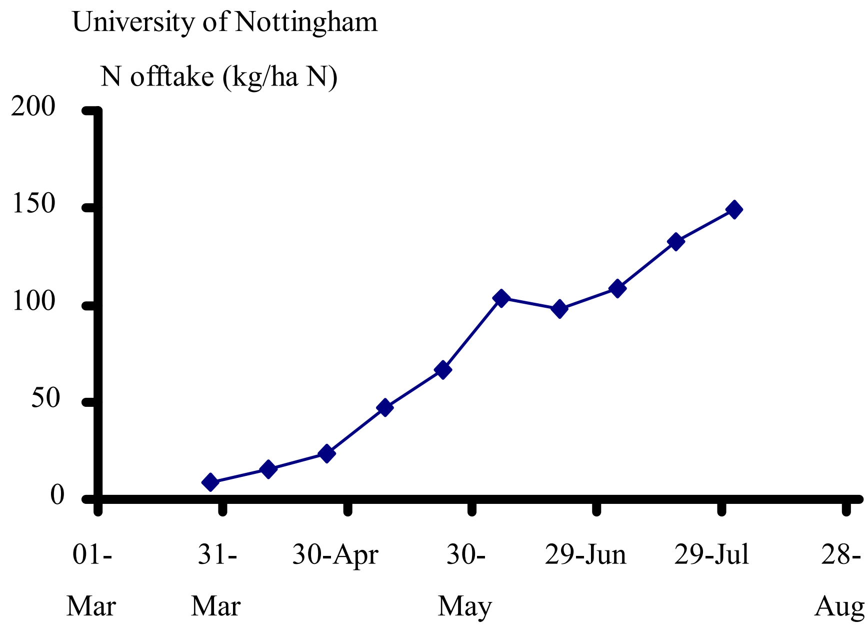


Figure 9 Uptake of N by unfertilised crops at the University of Nottingham and ADAS Boxworth in 1994. Data are means of sowing dates and N residues.



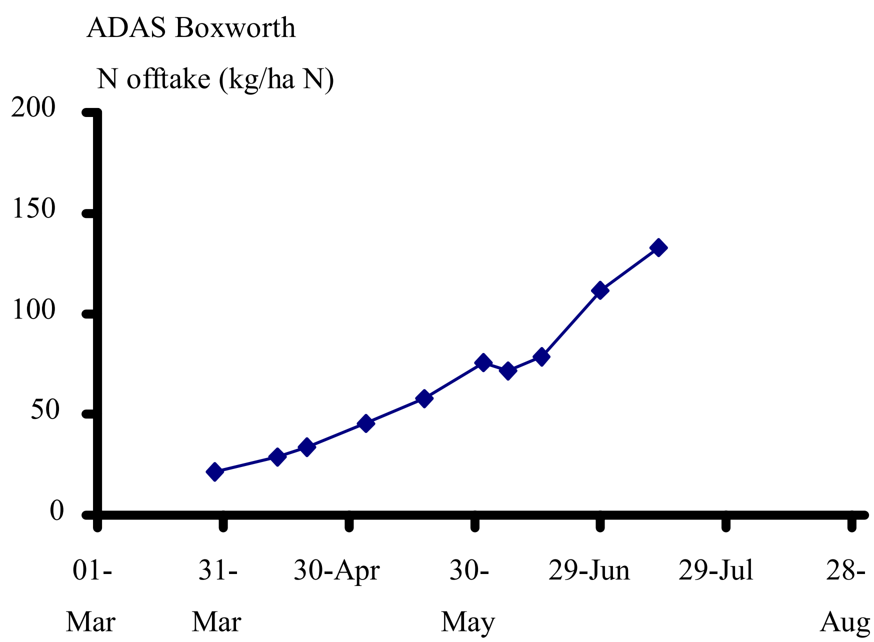
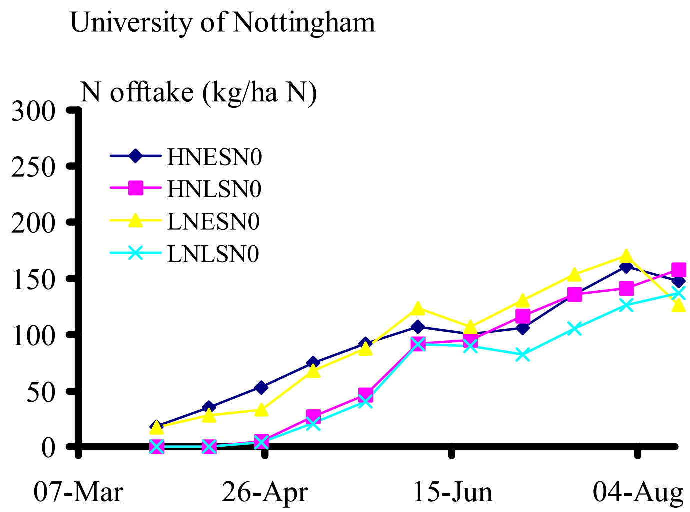


Figure 10 Uptake of N by unfertilised crops at the University of Nottingham and ADAS Boxworth in 1995. Data are means of sowing dates and N residues.



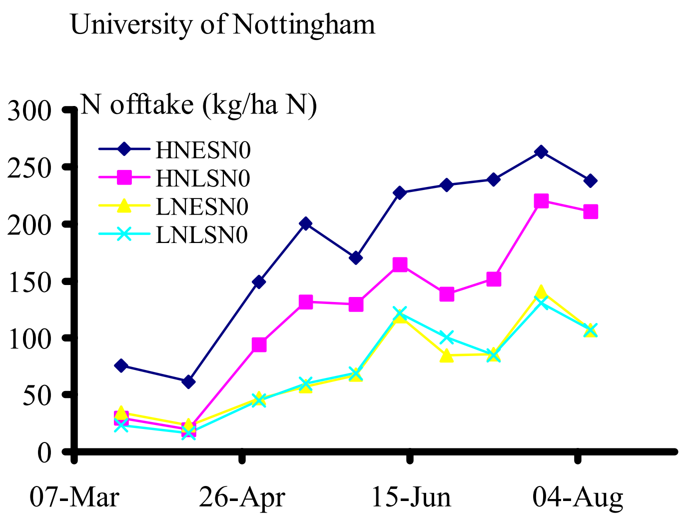


Figure 11 Uptake of soil mineral through the season at the University of Nottingham in 1994 and 1995. Data show uptake by individual background crops

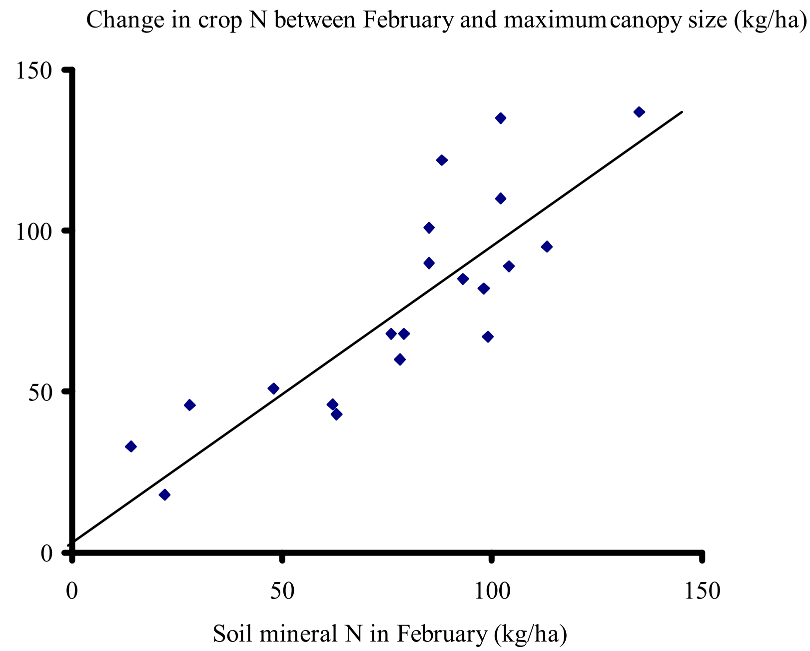


Figure 12 Relation between soil mineral N in February and crop N uptake from February to maximum canopy size.

In conclusion, this section on recovery of soil mineral N has demonstrated that the recovery can be predicted with accuracy and that an amount of N equivalent to the amount measured as ammonium and nitrate in early spring will be recovered by the time the canopy reaches maximum size. It therefore appears that the first component in the theoretical framework linking yield formation with N supply - the role of soil N - has a sound basis and has good potential to be used in commercially in winter wheat growing systems. Furthermore, the evidence for continued uptake of soil N well after flowering is important information having bearing on the production of grain for breadmaking.

N uptake - fertiliser N

Having examined the contribution of soil mineral N to N uptake, the next step in the process of linking the application of fertiliser to yield formation is to examine the contribution from fertiliser N. Evidence from Bloom *et al*. (1988) suggested that the recovery of fertiliser N by wheat can be variable, but on heavier, N retentive soils it is often near 60% This was used as the basis to predict the proportion of the fertiliser likely to be recovered and hence the amount of fertiliser N required to make good the shortfall in N supply from soil. In order to judge the timing of the applications of fertiliser N for Canopy Management, it was necessary to leave sufficient time between application and the end of canopy expansion to ensure that the N could be taken up. The minimum rate of uptake was estimated from the work of Widdowson *et al*. (xxxx) to be about 2kg/ha/day.

To determine the percentage recovery of fertiliser N and the minimum rate of uptake that could be expected for Mercia, firstly, it was necessary to make measurements where N supply was less restricted i.e. following conventional applications (30 kg/ha N in early March and the remainder, about 120 - 170 kg/ha, in mid April). And secondly, to make measurements where N supply was more restricted i.e. following Canopy Management where a greater proportion of the smaller amount of N was applied later in the season. Furthermore, it was necessary to identify the period when most of the N was taken up to determine N availability during canopy expansion. With Canopy Management, a significant proportion of the total N was applied either as granular ammonium nitrate or as foliar urea at anthesis. It was therefore necessary to examine the recovery of this late applied N to determine whether or not the Canopy Management approach affected the overall recovery of fertiliser N through change in recovery of N applied during canopy expansion, the N applied late to maintain canopy duration or both.

The uptake of fertiliser N will be examined in five parts:

1. the pattern of uptake through the season
2. the rate of N uptake during the period of rapid canopy expansion
3. the proportion of the fertiliser N recovered when the canopy reaches maximum size (available for canopy expansion)

4. the proportion of fertiliser N recovered by harvest (available for maintenance of the canopy and grain filling) and,
5. the proportion of the late N recovered by harvest

Uptake during the season

The effect of conventional N use and N use following the 'rules' for Canopy Management on crop N uptake are shown for the crops grown at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995 in Figure 13, Figure 14 and Figure 15 respectively. Data have been presented as means of sowing dates and N residues for each site / year combination and, the effects of sowing date and N residue are presented where the effects were largest i.e. at University of Nottingham in 1994 and 1995 in Figure 16 and Figure 17 respectively.

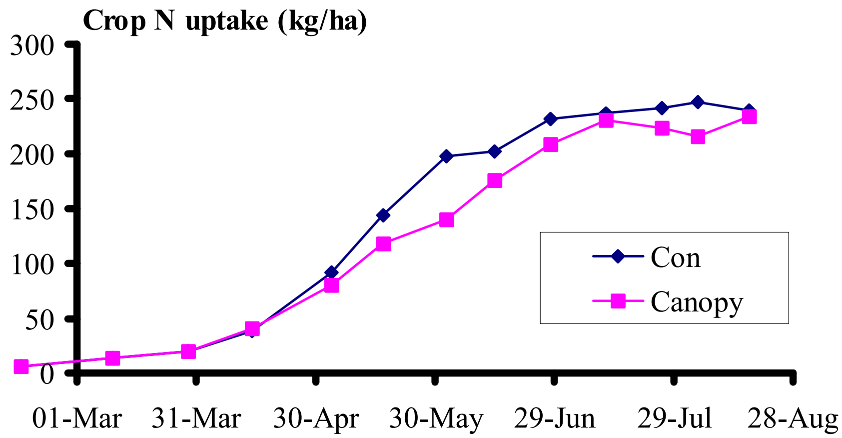
In 1993 at the University of Nottingham, N uptake in both the conventional and Canopy Management treatments continued until early July after which there was very little further uptake (Figure 13). During growth, consistently more N was taken up following conventional N use, however, there was no significant difference in N uptake at final harvest. At ADAS Boxworth in this year, the difference between conventional and Canopy management was more striking; with conventional N use, maximum uptake occurred before flowering whilst with Canopy Management N, uptake was more consistent, continuing into late July. At final harvest, there was no significant difference between the conventional and Canopy Management treatments.
In 1994, the pattern of N uptake was similar at both sites; Canopy Management restricted uptake consistently at each stage during the season but, at final harvest, there was no difference from conventional N use (Figure 14). At both sites N uptake continued until the latter stages of grain filling.
In 1995, there were no significant differences in uptake between treatments at either site (Figure 15). Uptake again continued through the grain filling phase, although at a slower rate.
The effects of sowing date on N uptake were smaller than expected. With conventional N, late sowing, on average, reduced the amount of N taken up at harvest from 235 to 228 kg/ha and with Canopy Management it was reduced from

216 to 214 kg/ha. The difference between sowings was largest at the University of Nottingham in 1994 (Figure 16). Here, late sowing in March, delayed the onset of N uptake until early May but thereafter the rate of uptake was faster resulting in total N uptake at harvest being 44 kg/ha less. More importantly, the pattern of N uptake was similar between sowings; Canopy Management resulted in less uptake during early growth but maintained uptake during grain filling resulting in similar amount of N taken up by harvest.

Soil N residue had very little effect on crop N uptake at harvest. On average across all crops at harvest, there was no difference between N residues; 245 kg/ha had been taken up. At the University of Nottingham in 1995 where the difference in soil N between residues (uptake by unfertilised crops) was largest, the pattern of N uptake was similar for conventional N and Canopy Management (Figure 17).

These results for N uptake through the season, provide important support for the concept of Canopy Management. It seems clear that it is possible to regulate fertiliser N supply to reduce N uptake during early growth but without compromising the amount recovered by final harvest. Also, it provides further support that although the majority of N applied to fertilised crops is taken up by flowering, there is still a significant proportion taken up during grain filling.

University of Nottingham 1993



ADAS Boxworth 1993

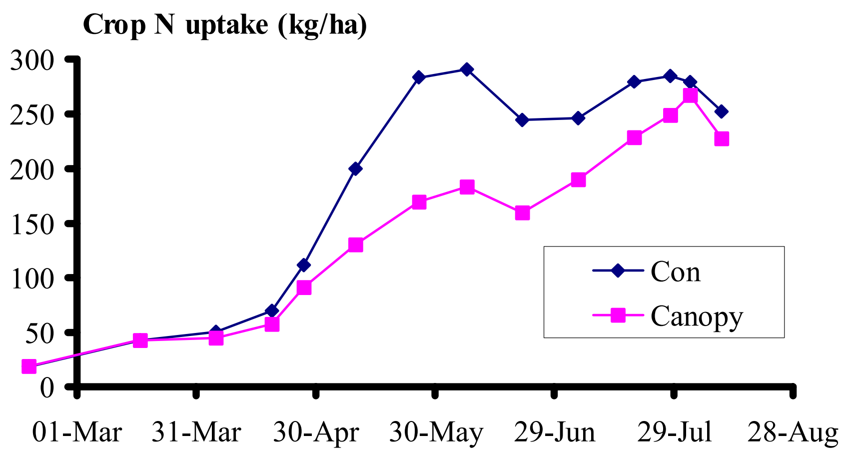
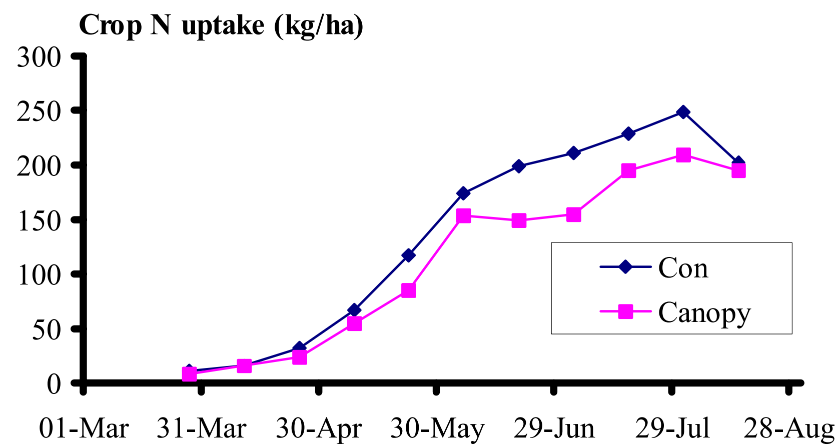


Figure 13 Crop N uptake at the University of Nottingham and ADAS Boxworth in 1993 following conventional (con) and Canopy Management (Canopy) fertiliser N use. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1994



ADAS Boxworth 1994

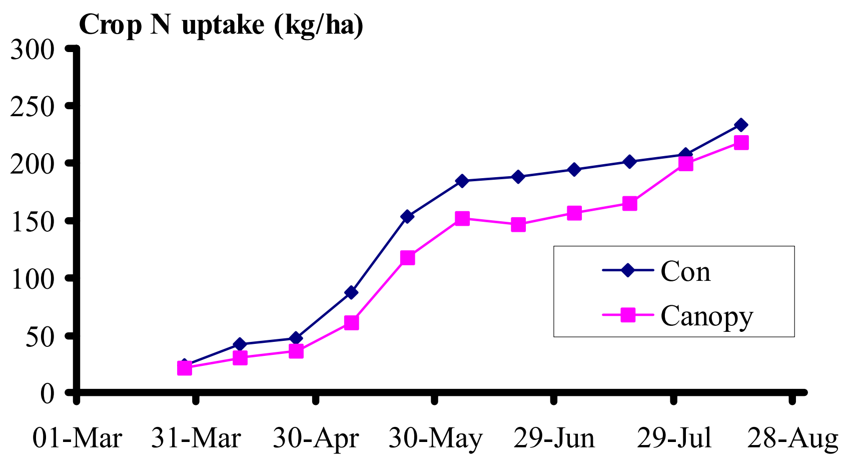
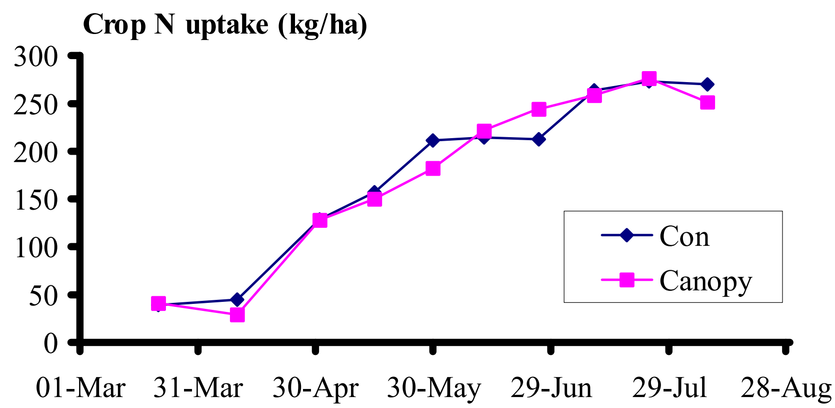


Figure 14 Crop N uptake at the University of Nottingham and ADAS Boxworth in 1994 following conventional (con) and Canopy Management (Canopy) fertiliser N use. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1995



ADAS Boxworth 1995

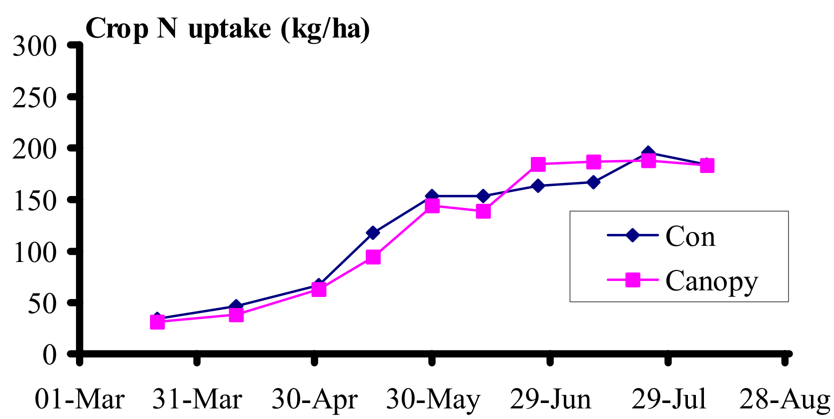
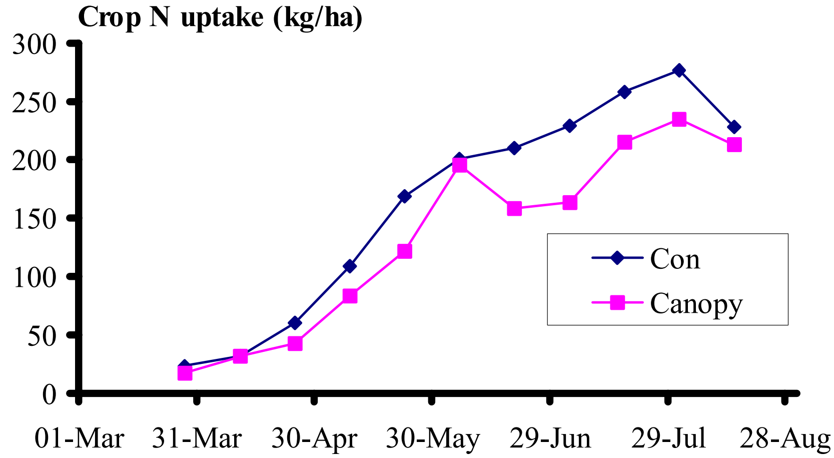


Figure 15 Crop N uptake at the University of Nottingham and ADAS Boxworth in 1995 following conventional (con) and Canopy Management (Canopy) fertiliser N use. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1994, early sowings



University of Nottingham 1994, late sowings

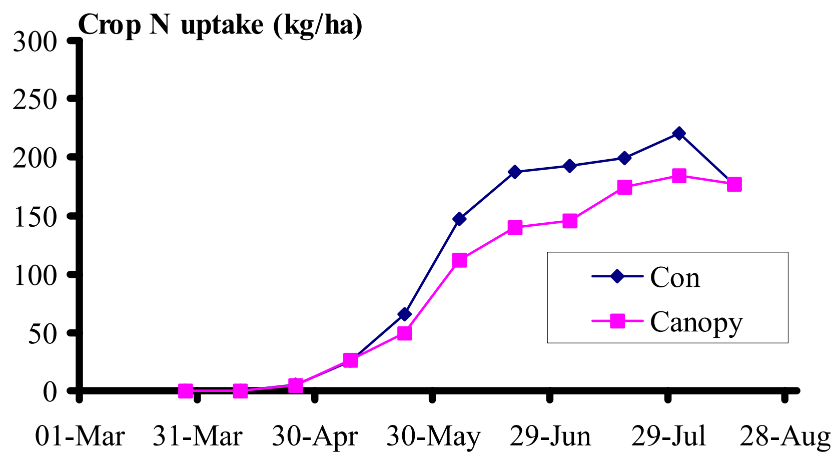
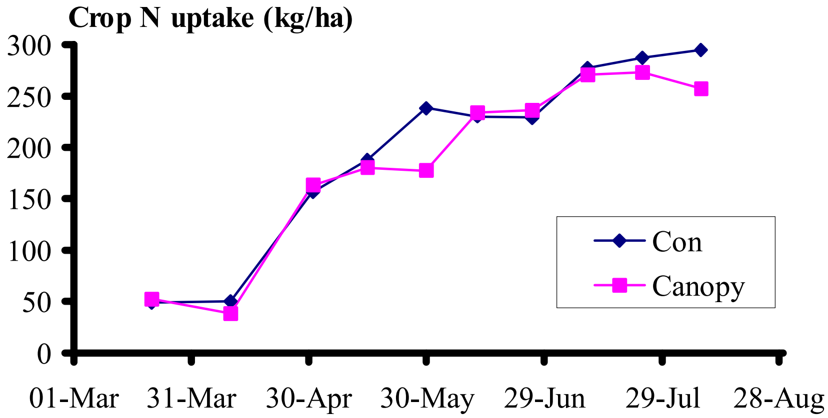


Figure 16 The effect of sowing early or late on crop N uptake following conventional and Canopy Management fertiliser N use at University of Nottingham in 1994. Data are expressed as means of N residues**.**

University of Nottingham 1995, High N residues



University of Nottingham 1995, Low N residues

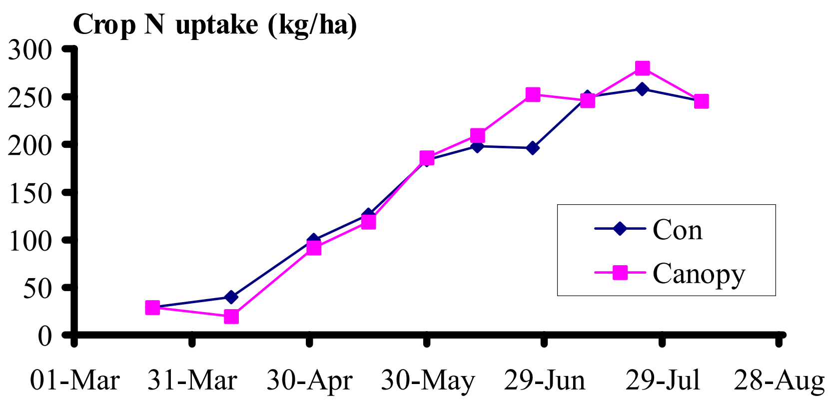


Figure 17 The effect of soil N residue on crop N uptake following conventional and Canopy Management fertiliser N use at the University of Nottingham in 1994. Data are expressed as means of sowing dates.

Rate of N uptake during canopy expansion

The overall rate of N uptake can be calculated by linear regression during the period of most rapid uptake. In these experiments, uptake was sometimes most rapid in the period before ear emergence whilst in some cases, significant uptake was maintained through to harvest and was almost linear over the whole season. In these situations, it is difficult to determine the beginning and end of a phase of uptake, even if crop development stages are used, the pattern of uptake may differ. To avoid these complications and to determine estimates of rate of uptake during canopy expansion, the rate of N uptake during the period of canopy expansion was calculated as the increase in N uptake between successive sample occasions divided by the time interval in days.

The rates of N uptake for the crops receiving conventional applications of N at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995 are shown in Table 19.

Table 19 The rate of crop N uptake during them season following conventional N use at the University of Nottingham (UN) and ADAS Boxworth (BX). Data are presented as means of sowing dates and N residues.

N uptake (kg/ha/day) *Conventional N use*	*UN 1993*	*BX 1993*	*UN 1994*	*BX 1994*	*UN 1995*	*BX 1995*	*Mean*
April (first half)	1.14	1.38	0.32	1.26	0.29	0.87	0.88
April (second half)	2.67	5.28	1.19	2.82	3.97	1.04	2.83
May (first half)	3.98	6.76	2.46	4.72	2.05	3.38	3.89
May (second half)	3.37	5.24	3.57	2.22	3.60	2.53	3.42
June (first half)	0.37	0.61	4.05	0.63	0.24	0.02	0.99

Rates of N uptake were generally small in early April, averaging 0.88 kg/ha/day but were variable ranging fourfold from 0.29 to 1.38. In late April, rates increased to on average 2.8 kg/ha/day. The average rate of uptake at the University of Nottingham in

1994 was low mostly due to the late sown crop which did not take up appreciable amounts of N until early May. The maximum rates of uptake occurred in early May and these were maintained through to late May. Rates of uptake were markedly lower in early June when canopies had reached maximum size and soils were drying out. It appears from these data that where N supply is less restricted (conventional N use rather than Canopy Management) that the proposed 'rule' allowing for a minimum rate of uptake of 2 kg/ha/day, was exceeded in all crops during May when canopy expansion is fastest and thus 2kg/ha/day therefore appears to be a suitably conservative figure for judging safe application dates.

In contrast with conventional N use, average rates of N uptake following Canopy Management were more consistent throughout the season in particular uptake in June was over 1 kg/ha/day greater. These data provide support for the Canopy Management approach; they demonstrate that rate of uptake can be regulated by N amount and timing and, that application of N later in the season can maintain relatively rapid rates of uptake.

Table 20 The rate of crop N uptake during them season following conventional N use at the University of Nottingham (UN) and ADAS Boxworth (BX). Data are expressed as means of sowing dates and N residues**.**

N uptake (kg/ha/day)							
Canopy Management N use							
	UN 1993	*BX 1993*	*UN 1994*	*BX 1994*	*UN 1995*	*BX 1995*	*Mean*
April (first half)	1.30	0.92	0.50	0.61	-0.58	0.49	0.54
April (second half)	1.98	4.19	0.57	1.79	4.69	1.23	2.41
May (first half)	2.89	3.01	2.23	4.04	1.58	2.13	2.65
May (second half)	1.37	2.44	2.18	2.42	2.13	3.54	2.35
June (first half)	2.97	1.12	4.86	1.19	3.08	-0.35	2.14

Recovery of fertiliser N at maximum canopy size

The objective of Canopy Management is to provide a rationale with which to apply fertiliser N to make good the shortfall between soil N supply (quantified earlier in this section) and the amount of N uptake required to attain the target size of canopy. It is therefore necessary to determine the contributions to N uptake from both soil and fertiliser and then determine the proportion of fertiliser N recovered by the time maximum canopy size is attained. The recovery of fertiliser N can be measured by comparing fertilised crops with unfertilised crops. Thus the difference is the 'apparent' recovery from fertiliser N. Apparent recoveries of fertiliser N were calculated as the difference in N uptake between the fertilised and unfertilised crop expressed as a proportion (%) of the fertiliser N applied. Table 21 shows the apparent recoveries for conventional N use and Canopy Management. Also, the estimate if the amount of fertiliser N left unrecovered in the soil is presented.

Table 21 Apparent recovery of fertiliser N at maximum canopy size at Sutton Bonington and ADAS Boxworth in 1993, 1994 and 1995 and the estimated amount of fertiliser N left unrecovered. Data are means of sowing dates and N residues.

Site and year	Apparent recovery at maximum canopy size (%)		Estimated amount of fertiliser N not recovered by maximum canopy size (kg/ha)	
	Conventional N	*Canopy N*	*Conventional N*	*Canopy N*
UN 1993	60	66	78	38
UN 1994	50	82	89	18
UN 1995	47	31	87	81
BX 1993	95	67	10	18
BX 1994	67	76	54	26
BX 1995	42	30	93	109
Mean	*60*	*59*	*68*	*48*

The apparent recoveries of fertiliser N were variable, ranging from 30 to 95%. This is slightly wider than the expected range of 40 to 80%. The smallest recoveries occurred in the drier year 1995 at both sites and in these situations, Canopy Management resulted in slightly poorer recoveries. These calculations do not include the late N applied at flowering to the canopy management treatments. However, the fertiliser N applied for expansion of the canopies in the canopy management treatments was generally applied later in the season than was the case with conventional N use and hence would be more prone to poor uptake but over all seasons, the recovery of fertiliser N at maximum canopy size was not significantly different between conventional N and Canopy Management, averaging 60% which is exactly the figure taken from the literature at the start of this project. The next stage in this analysis (to be reported elsewhere) is to examine for any underlying causes of particularly poor and good uptake so that some of the variation around 60% might be explained.

Canopy Management resulted in less fertiliser N remaining in the soil at the time maximum canopy size was reached because, by this stage, less N was applied than with conventional use.

Recovery of fertiliser N at harvest

Although Canopy Management had little overall effect on apparent recovery at maximum canopy size, N was applied after this at flowering, to maintain canopy duration. Analysis of apparent recovery at final harvest provides a means for determining the recovery of all the fertiliser N applied. Apparent recoveries of fertiliser N with conventional use and Canopy Management for the crops at the University of Nottingham and ADAS Boxworth in all years is presented in Table 22 together with the estimated amounts of fertiliser N unrecovered.

Table 22 Apparent recoveries of fertiliser N at harvest with conventional N use and with canopy management (including 60 kg/ha N applied late at flowering) and the estimated amount of fertiliser N left unrecovered.

Site and Year	Apparent recovery at final harvest (%)		Estimated amount of fertiliser N not recovered final harvest (kg/ha)	
	Conventional N	*Canopy N*	*Conventional N*	*Canopy N*
UN 1993	45	51	106	84
UN 1994	33	36	115	92
UN 1995	56	57	75	79
BX 1993	64	68	59	36
BX 1994	65	55	56	75
BX 1995	40	40	95	131
Mean	*50*	*51*	*84*	*83*

The apparent recoveries were less variable than at maximum canopy size ranging from 33% to 68% (Table 22). Overall, there was no significant difference between conventional N and Canopy Management; the average apparent recoveries were 50 and 51% respectively. The apparent recoveries were smaller than at maximum canopy size. With conventional N use, this probably resulted from continued uptake by unfertilised crops which in most cases continued well into the grain filling period. With Canopy Management, the lower recovery may be also have resulted from poor recovery of the late N applied at flowering.

Following the application of late N to the canopy management treatments, the average amount of fertiliser N left unrecovered was similar to that left after conventional N use, just over 80 kg/ha N.

Recovery of the N applied at flowering

The apparent recovery of the fertiliser N applied late at flowering can be calculated in 1994 and 1995 only. This is possible because, in these years, Canopy Management was tested with and without the late N at flowering. Thus Canopy Management without late N provides the baseline for assessing uptake from soil N after flowering in the Canopy Management treatments.

The apparent recovery of the late application of 60 kg/ha N at flowering was generally poor, averaging just 25% (Table 23). At the University of Nottingham in 1994 soils were very dry at anthesis but substantial rain was forecast for a 3 to 4 day period. N was applied in granular form but no rain fell. Recoveries of granules were particularly poor in very dry conditions at the University of Nottingham in 1994 and ADAS Boxworth in 1995. However, use of foliar N at the University of Nottingham in 1995 partially overcame the dry conditions and recovery was 46%, the same as the recovery at ADAS Boxworth in 1994 when soils were wetter in June. There was no consistent effect of site, sowing date nor N residue on the apparent recovery of the late N; high N residues had on average slightly larger recoveries (30.6% compared with 25.2% for smaller N residues) and sowing date had a negligible effect (early sowings, 29.1% compared with 31.2% for late sowings). These relatively poor recoveries, especially with the use of foliar N, were unexpected. Examination of the recoveries from all the sites where conventional N and Canopy Management were compared showed a similar trend; N residue and sowing date affected recovery by on average only 2 percentage points. These averages conceal marked differences in recovery of late applied N though, for individual crops, recoveries varied from -29% up to 124%. This variable response coupled with the lower than anticipated average recovery require further investigation. Furthermore, that N residue and sowing date have relatively minor effects overall suggest that the explanation will most likely come from analyses of crop structure and activity at N application. This was the focus of the work conducted at IACR Rothamsted .

Table 23 The apparent recovery of the fertiliser N applied late at flowering to the Canopy Management treatments in 1994 and 1995. Data are means of sowing dates and N residues.

Site and year	Apparent recovery at final harvest of the N applied flowering (%)
UN 1994	6 granules
UN 1995	46 foliar
BX 1994	42 granules
BX 1995	7 granules
Mean	*25*

These results for the recovery of spring-applied fertiliser N are encouraging. N uptake with Canopy Management was more consistent over the season; the rate of uptake was usually less than with conventional N but this more moderate uptake continued for longer during the grain filling phase. This is consistent with the underlying philosophy of Canopy Management.
Furthermore, the values for apparent recovery and rates of minimum uptake found within these field tests on Mercia are consistent with our initial estimates of 60% and 2 kg/ha/day respectively. The recovery of the late applied N however, was disappointingly low and the reasons for this require further investigation.

Studies on the efficiency of uptake of N from foliarly-applied urea

When late nitrogen is applied to the soil as prilled ammonium nitrate, movement into the crop is often slow - especially in dry years - and the efficiency of uptake often averages less than 60%. Use of foliar applied N sometimes improves uptake but is far from reliable. Evidence from the Field Tests of canopy Management has confirmed this. Studies at IACR-Rothamsted were conducted to identify why this should be so and potential areas for improvement. The investigations examined the spatial deposition and dynamics of uptake of foliarly-applied urea within winter wheat canopies of different size and structure. In this Report, only the main findings from this work are presented. A more complete analysis and discussion is reported elsewhere (Hopkinson, 1997).

Experimental crops, differing in canopy size, were produced through differential basal N fertiliser treatments (see Materials and Methods in this report for full details). Crops were unfertilised, fertilised conventionally (Conventional) or fertilised according to Canopy Management (Canopy). Foliar urea was applied to some or all of these crops at two rates (30 or 60 kg/ha) at flag leaf emergence, GS 39; ear emergence, GS 59; or during anthesis, GS 65). In some comparisons, N was also applied with to examine their effect on spread, retention or penetration of the foliar N solution. These additives were: Silwet L-77 (a spreader), Spray-fix (a sticker) and LI-700 (a penetrant).

The spatial deposition of the applied urea and its relation to leaf size and position within the canopy were determined immediately after spraying on a random sample of shoots taken a immediately after spraying (t_0) and stratified into different leaf/stem layers (ear, flag leaf, flag leaf-1, etc.). The urea present in each layer was washed from the leaf/stem surfaces by washing for 10 minutes in a known volume of detergent (0.1% Triton X-100) and chemically analysed. The green area, dry weight and nitrogen content of the plant material within each layer was measured after washing. The dynamics of N uptake from foliar urea during the 96 hours following spraying were monitored in a similar manner on flag leaves that were sampled at frequent intervals.

The approach, especially its application to the study of the dynamics of uptake, was validated by experiments under controlled conditions with ^{15}N-labelled urea applied to the flag leaf (Figure 18). These confirmed that of the N deposited on the leaf surface, approximately 16% was not recovered either within the washing solution or the plant within minutes of spraying (t_0). A further 16% was lost slowly during the following 96 hours (t_{96}), possibly through chemical volatilisation. 66% of foliarly-applied N was therefore present on the leaf at t_0, and 22% remained on the leaf surface after 96 hours. 45% of the applied ^{15}N appeared within the plant, mostly within the first 24 hours. The disappearance of urea from the leaf surface, monitored by the washing technique, paralleled the appearance in the plant. The method therefore provided a reasonable indication of uptake.

Spatial deposition of urea within the canopy.

Typical patterns for the distribution of the foliar urea N within the canopy at t_0 and t_{96} are shown in Figure 19 for a Canopy Management crop to which 30 kg urea N/ha had been applied at ear emergence. In addition, the deposition of urea (expressed as the accumulated percentage of the amount applied present in successive layers down the canopy profile) is plotted against the corresponding accumulated green area index for a series of Canopy Management crops treated with foliar-urea sprays combined with different adjuvants in Figure 20, and for a series of crops grown with different basal N treatments in Figure 21.

Exponential asymptotic equations of the form $y = A + Be^{-kx}$ were fitted to the deposition curves and used to derive the values for the total proportion of applied urea N initially deposited on the crop canopy ($N_{t=0}$). These are given in Table 24. The unfertilised crop produced a much smaller leaf canopy (GAI = 1.8) than the conventional and Canopy Management crops, which were of similar size (GAI *ca* 5.0). The washing study showed that only *ca* 60-65% of the applied urea was present on surfaces within the canopy. Part of the loss could have been due to turbulent transfer of spray droplets away from the sprayed area. The unfertilised, Conventionally fertilised and Canopy Management crops treated with urea sprays containing the spreader (Silwet L-77) and penetrant (LI-700) adjuvants, intercepted and retained significantly less of the applied urea. Increased leaf angles in the unfertilised crops, greater leaf waxiness in the Conventionally fertilised crops together with the lower surface tension of the spray film where the additives were used might all have exacerbated losses through run-off. Approximately 90% of the N deposited on the crop at spraying had gone from the surfaces within 96 hours (Table 24).

Table 24 Maximum green area index (GAI_m), the percentage of applied foliar N deposited on the crop at spraying ($N_{t=0}$), the percentage of the applied N remaining after 96 hours ($N_{t=96}$), the percentage of deposited N assumed to have been taken up (U%), and the half-time (h) for uptake by the flag leaf ($t_{0.5}$).

Treatments			Foliar-applied N				
Basal N	Foliar N		Deposition		**Uptake**		
	kg/ha	Adjuvant	GAI_m	$\mathbf{N_{t=0}}$	$N_{t=96}$	U%	$\mathbf{t_{0.5}}$
Ear emergence (GS 59)							
Canopy	30	nil	5.21	62.7	6.7	89.1	11.8
Canopy	30	Silwet L-77	5.05	36.7	4.0	88.7	13.8
Canopy	30	Spray Fix	5.29	57.8	5.1	90.8	19.9
Canopy	30	LI-700	4.94	43.3	5.8	86.7	16.5
Anthesis (GS 65)							
Canopy	30	nil	4.79	64.5	4.3	93.2	9.8
Canopy	60	nil	4.49	51.7	5.4	89.3	32.4
Canopy	30	Silwet L-77	4.64	37.1	6.5	81.9	-
Unfertilised	30	nil	1.78	26.4	8.9	65.6	28.0
	30	nil	5.00	35.9	9.3	73.9	43.2
Conventional							
SED (16 df):			0.375	8.89	1.19 *	4.44 ***	8.66

Dynamics of uptake.

These were studied in more detail, by using the washing technique on flag leaves sampled at frequent intervals after spraying. The changes with time in the amounts of urea N remaining on the leaf surface (expressed as a percentage of that present at t_0) are shown in Figure 22 for crops grown with the different basal fertiliser treatments. Exponential decay curves were fitted to the data, from the coefficients of which the time required for half of the deposited urea N to disappear ($t_{0.5}$) were calculated (Table 24). The half-times were generally within the range of 10 - 15 hours, except for unfertilised, conventionally fertilised and the Canopy Management crops to which the equivalent to 60 kg N/ha of urea had been applied in which the half-times for uptake were much longer.

Figure 18 Changes with time in the amounts of urea N remaining on the surface of flag leaves of unfertilised (□), Conventionally fertilised ( ) and Canopy Managed (o) crops treated with 30 kg/ha, and of a Canopy Managed crop treated with 60 kg/ha (.) at anthesis.

Figure 19 Changes with time in ^{15}N (as a percentage of that applied) washed from the leaf surface ( ), present in the plant ( ), and totally accounted for ( ).

Figure 20 The spatial deposition of foliar urea applied to the canopy of a GAI_5 crop at flag-leaf emergence (GS 39) at the time of spraying and 96 hours afterwards.

Figure 21 The relation of deposition of foliarly-applied N to accumulated GAI down the canopy profile for GAI_5 crops treated with 30 kg foliar urea/ha at ear emergence with no adjuvant ( ), or with Silwet L-77 ( ), Spray Fix ( ) or LI-700 ( ).

Figure 22 The relation between deposition of foliarly-applied N and accumulated GAI down the canopy profile after application of 30 ( ) or 60 ( ) kg/ha applied to Canopy Management crops at ear emergence, and 30 kg/ha applied to unfertilised ( ), Conventionally fertilised ( ) and Canopy Management crops ( ) at anthesis.

Summary.

This part of the programme has highlighted some of the limitations to the uptake of foliar N by winter wheat canopies. Only 65% of the applied urea N was present on the leaf canopy immediately after spraying, the remaining 35% either did not reach the canopy, passed through to soil or was degraded extremely rapidly on the surface of the crop. The proportion adhering to the crop appeared to be decreased by run-off when adjuvants that reduce the surface tension of the spray film were used. The efficiency of uptake (measured either as the proportion taken up or the rate of uptake) was not a major limiting factor; about 90% of the deposited N was taken up within 24 hours of application. Generally, canopies of crops with a GAI of 5 were more efficient than those of the unfertilised and conventionally fertilised crops. The latter not only intercepted and retained a smaller proportion of the applied foliar N (25-35%), but took up less of it (65-75%), and at a slower rate ($t_{0.5}$ 30-40 hours).

Table 25 summarises the broad pattern of losses of N between spraying and uptake by the crop. It is clear from this work that significant improvements in efficiency of foliar N use are likely to result from firstly identifying the causes of the losses between spraying and deposition on crop and secondly from understanding the reasons for loss of N from the leaf surface (but which is not taken up) and, why part of the N remains on the leaf after 4 days . Thus there should be focus on application technology as well as physiological investigations into N uptake after application.

Table 25 Losses of N between spray boom and crop uptake. Losses are expressed as a percent of that leaving the boom.

Leaving spray boom	100
N not deposited on crop immediately after spraying	35
N lost from crop surface within minutes of application	10
N lost from crop surface over 4 days	10
Uptake by crop	30
Remaining on crop surface after 4 days	15

This section on N uptake by crops (from both soil and fertiliser) has provided valuable supporting evidence for the 'rules' 3, 9 and 10. Furthermore, the analyses from the foliar N studies have revealed the magnitudes of the sites of failure between spraying and uptake and showing that the could be significant benefit from improvements in application technology as well as improvements in understanding the physiology of N uptake from the crop surface.

Canopy expansion

Having established that it is possible to quantify N supply from both soil and fertiliser. The next step in this examination of the processes between N application and yield formation is to examine the relationship between uptake of N and canopy expansion. This is the crucial step in the physiological framework presented in Figure 2 as it forms the junction between the work of soil scientists and crop scientists.

Canopy nitrogen requirement

The uptake of N to form a unit of green canopy area can be described as the Canopy Nitrogen Requirement (CNR). Sylvester-Bradley *et al*. (1990) suggested this was 30 kg N uptake to form each hectare of green surface in the winter wheat variety Avalon. The concept of CNR has not been validated and the aim of this section is to examine the evidence for the relationship between N uptake and canopy expansion and, to determine whether or not 30 kg/ha is the most appropriate CNR for Mercia. The link between N uptake and canopy expansion was examined for the crops grown at the University of Nottingham and ADAS Boxworth.

An example of the dependence of canopy expansion on N uptake is shown in (Figure 23) for the unfertilised crops and the conventionally fertilised crops at ADAS Boxworth in 1993. These data extend over the period of canopy expansion between February and late May. The data are from early and late sowings on high and low soil N residues. During canopy expansion, N uptake appears to strongly control canopy size; the relationships were highly significant, linear and intercepts usually not statistically significant, thus the lines were forced through the origin. There was however, a significant difference in the gradient of the line between unfertilised crops and conventionally fertilised crops, inferring that where fertiliser was applied, the CNR was different. For example, the CNR for the conventionally fertilised crops was 29 (kg/hectare N uptake per hectare green surface) whereas the unfertilised crops appears to use N more efficiently, with a CNR of 25. This appeared to be a consistent finding. Table 26 shows the CNR for the crops grown at the University of Nottingham and ADAS Boxworth in 1994.

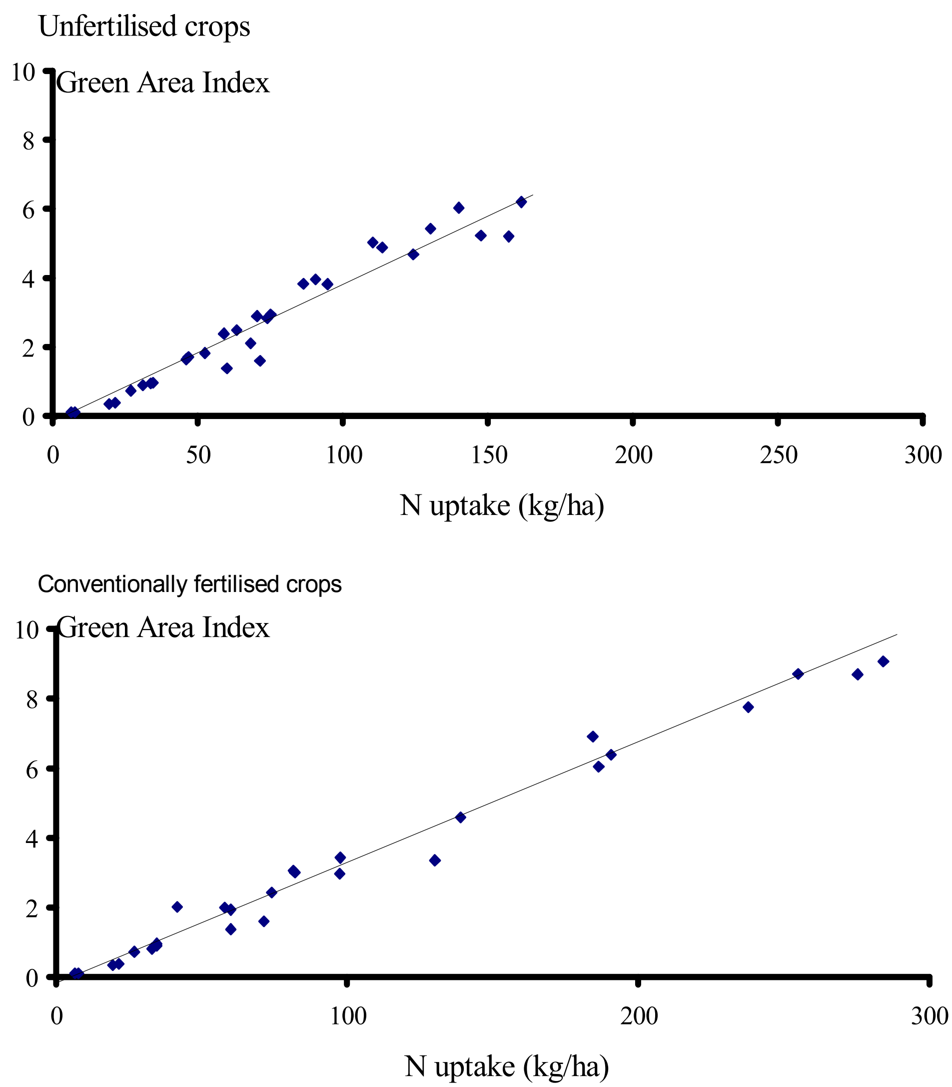


Figure 23 The relationship between N uptake and canopy size for both fertilised and unfertilised crops ADAS Boxworth in 1993.

Table 26 Canopy nitrogen requirement (kg/hectare N uptake per hectare green surface) during canopy expansion at the University of Nottingham and ADAS Boxworth in 1994.

Site and test crop	*Unfertilised*	*Conventional N*
High N Early sown	21.2	26.6
High N Late sown	23.8	30.4
Low N Early sown	20.7	28.7
Low N Late sown	32.2	30.3
Mean	24.5	29.0
High N Early sown	24.7	27.0
High N Late sown	23.6	25.7
Low N Early sown	26.6	29.3
Low N Late sown	24.9	26.7
Mean	25.0	27.1

Whilst these results are encouraging and support the existence of a canopy nitrogen requirement, it was variable especially with respect to fertilised and unfertilised crops. The lower CNR of unfertilised crops suggest that they use N more efficiently to form canopy. This is difficult to explain because it infers that unfertilised crops which can only take up soil N, use this N in some different way from fertiliser N. This is unlikely since N enters plant roots in either nitrate or ammonium form irrespective of source.

There are two potential problems with analysing for CNR where cumulative values are regressed as the crop grows through the season. Firstly, when cumulative data sets are regressed, straight lines often result. Also, statistical tests are not valid because the sets of data points are not strictly independent and furthermore, canopy nitrogen requirement is confounded with stage of growth and calendar date.

An alternative and more robust test of the Canopy Nitrogen Requirement is to uncouple the confounded effects of crop growth stage with canopy size and N uptake. This has been achieved by plotting the maximum canopy size (or when canopy size tended to plateau out) with crop N uptake at that time for all the sets of data available from the University of Nottingham and ADAS Boxworth for all three years. The results are shown in Figure 24.

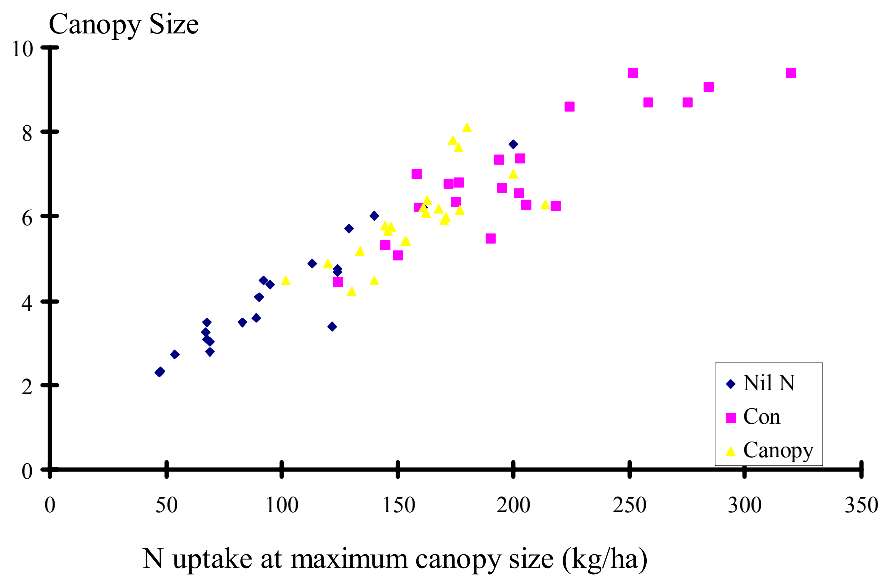


Figure 24 The relation between maximum canopy size and crop N uptake for unfertilised crops (Nil N), conventionally fertilised crops (con) and canopy management (canopy) at the University of Nottingham and ADAS Boxworth in all years.

Figure 24 shows the robustness of the concept of CNR; N uptake was responsible for 87% of the variation in maximum canopy size. This is remarkable considering the wide range of background crops which formed the tested for Canopy Management. Furthermore, the data sets from the unfertilised crops now fall on the same line as the fertilised crops showing, as we would expect, there was no fundamental difference in the way crops used soil N or fertiliser N to form canopy. When N uptake was regressed against canopy size separately for the normal N, canopy management and unfertilised crops, the lines were not statistically different thus providing more evidence that the same canopy nitrogen requirement can be used for all crops. It must be remembered however, that this may not hold at excessively high rates of N where luxury uptake of N may occur.

The line of best fit describing the CNR for Mercia is:

$$\text{Canopy size} = (0.028 \times \text{N uptake}) + 1.36$$

The existence of the significant intercept means that the amount of N required to produce a hectare of green surface will change depending on canopy size. For example, the amount of N uptake required for each hectare of green surface for crops of different size is shown in Table 27.

Table 27 The effect of canopy size on the amount of N required to form each hectare of green canopy.

Canopy size	kg/hectare N per hectare of green canopy	Total N uptake required (kg/hectare)
4	23.6	94
5	26.0	130
6	27.6	166
7	28.8	202
8	29.6	237
9	30.3	273

Evidence from Table 27 shows that whilst the relation between N uptake and canopy size is linear it takes 26 kg/hectare N uptake to produce each hectare of canopy for a canopy with 5 hectares of green surface per hectare of land whereas it takes 30 kg/hectare N uptake to produce each hectare of canopy, in a crop with 9 hectares of canopy per hectare of land. This shows that, whilst the concept of a constant canopy nitrogen requirement of 30 kg/hectare N was incorrect, the presence of a direct relationship was substantiated. This result is encouraging because it provides the basis with which to relate a prescribed size of canopy to the amount of N uptake required. This then can be related to supply from soil and contribution from fertiliser N.

The effect of fertiliser treatment on the maximum size of the canopies produced at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1994 is shown in Table 28. In all but 3 of the 22 comparisons where Canopy size was measured, Canopy Management reduced maximum size. In two cases, canopies were the same maximal size and in 1 case Canopy Management resulted in a slightly larger canopy (0.7 GAI larger). The overall reduction in Canopy size was 1.1 GAI but the mean maximum canopy size following Canopy Management was 6 GAI, 1 unit of GAI larger than the original target in set out in the Introduction. This overshoot was most probably the result of using the figure of 30 kg/ha per unit GAI for the crop's canopy N requirement (CNR). It was shown in sections on canopy expansion that the CNR for GAI 5 in Mercia was 26 kg/ha/GAI. This would account for an overshoot of approximately 0.75 units of GAI; close to what was observed.

It is important to note that the canopies following Canopy Management were less variable as shown by the standard errors in Table 28. Thus it appears that the Canopy management approach can be used to successfully limit canopy size especially if the revision for CNR is adopted. However, the promising yield responses resulted from canopies which were slightly larger than target and thus a further objective must be to determine whether canopies closer to GAI 5 will produce yields similar to those resulting from the canopies of GAI 6 reported here.

Table 28 The effect of Canopy Management on maximum canopy size at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995.

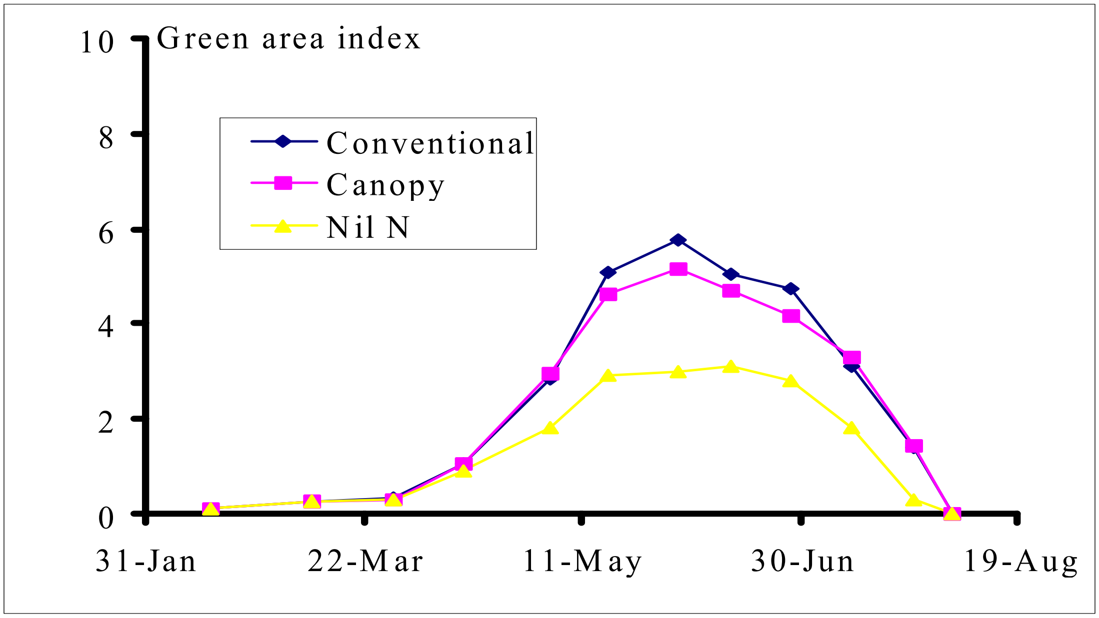
Year	Site	Background Crop	*Conventional*	*Canopy*	*Nil N*	Reduction through Canopy Management

1993	UN	HNES	6.2	5.4	3.5	-0.8
		HNLS	5.3	4.9	3.1	-0.4
		LNES	6.3	5.8	2.7	-0.6
		LNLS	5.5	4.5	3.0	-1.0
1993	AB	HNES	9.4	6.4	6.2	-3.0
		HNLS	8.7	7.6	6.0	-1.1
		LNES	8.7	5.9	4.7	-2.8
		LNLS	9.1	6.2	4.9	-2.9
1994	UN	HNES	6.8	6.2	4.5	-0.7
		HNLS	7.4	5.2	4.4	-2.2
		LNES	6.7	6.3	4.7	-0.4
		LNLS	6.8	5.7	4.1	-1.1
1994	AB	HNES	6.6	5.4	3.6	-1.1
		HNLS	6.2	6.2	3.5	0.0
		LNES	7.0	6.1	2.3	-0.9
		LNLS	7.3	5.7	2.8	-1.6
1995	UN	HNES	9.4	8.1	7.7	-1.3
		HNLS	8.6	7.8	5.7	-0.8
		LNES	8.0	6.0	3.3	-2.0
		LNLS	6.3	7.0	3.4	0.7
1995	AB	HNES	4.4	4.5	3.5	0.0
		LNES	5.1	4.2	2.3	-0.9
		Mean (se)	*7.1 (0.31)*	*6.0 (0.22)*	*4.1 (0.30)*	*-1.1*

The effects of Canopy Management on control of canopy size is shown as means of the individual test crops for the University of Nottingham and ADAS Boxworth in 1993 (Figure 25), in 1994 (Figure 26) and in 1995 (Figure 27).

The effect of the late applied N on canopy prolongation is shown in Figure 28 and Figure 29 for 1994 and 1995 respectively. On average, the application of late N did little to improve canopy prolongation emphasising the need to further investigate the utilisation of late N by wheat crops.

University of Nottingham 1993



ADAS Boxworth 1993

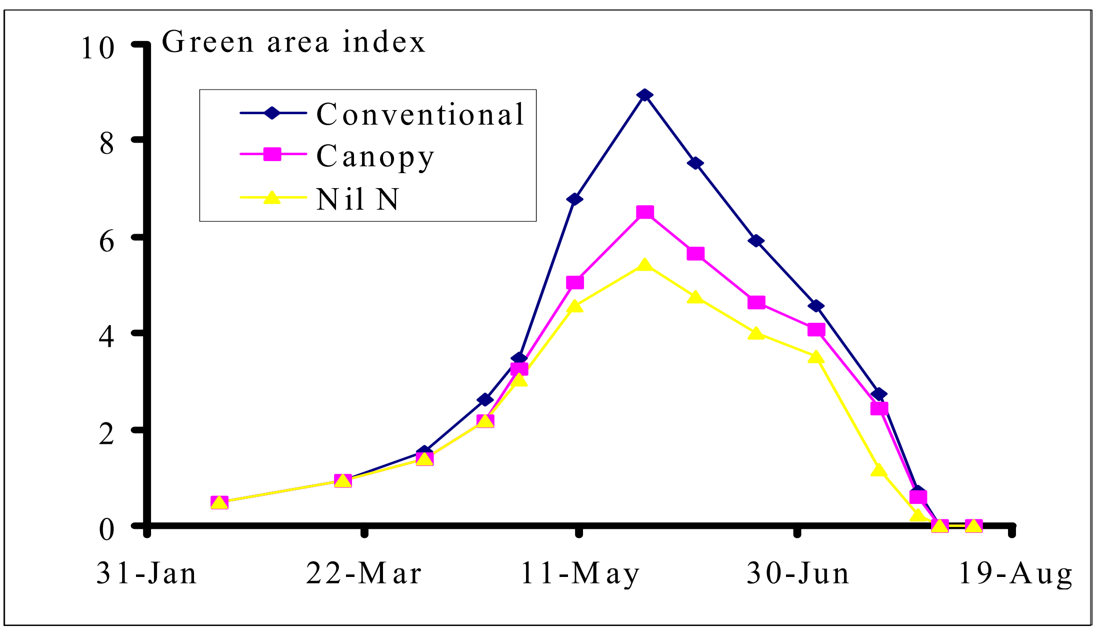
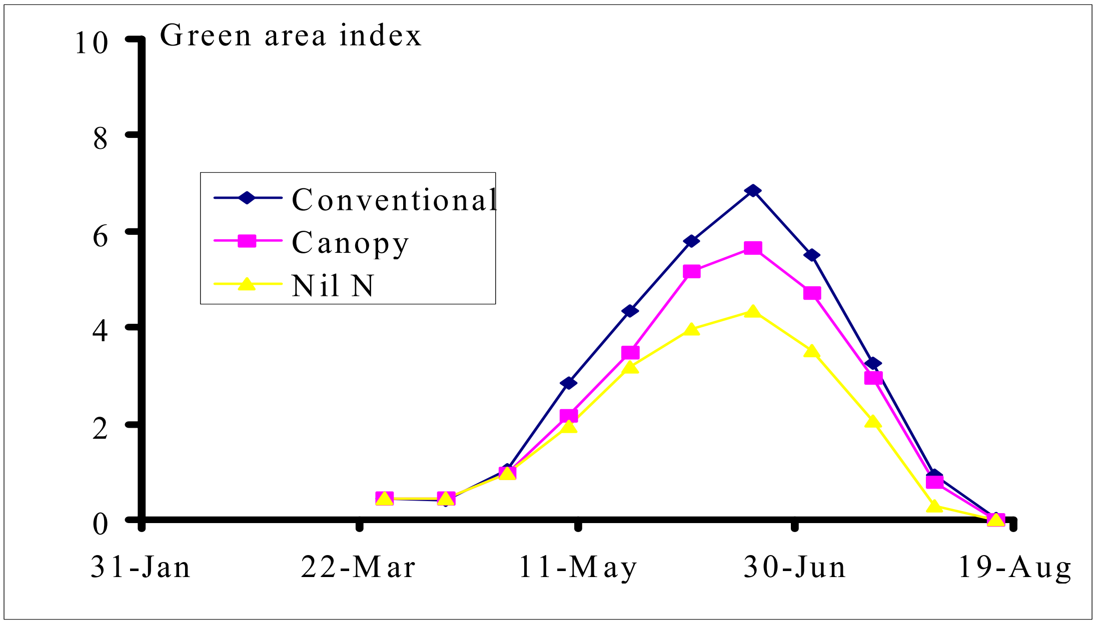


Figure 25 The effect of Conventional, Canopy and Nil fertiliser N applications to crops grown at University of Nottingham and ADAS Boxworth in 1993. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1994



ADAS Boxworth 1994

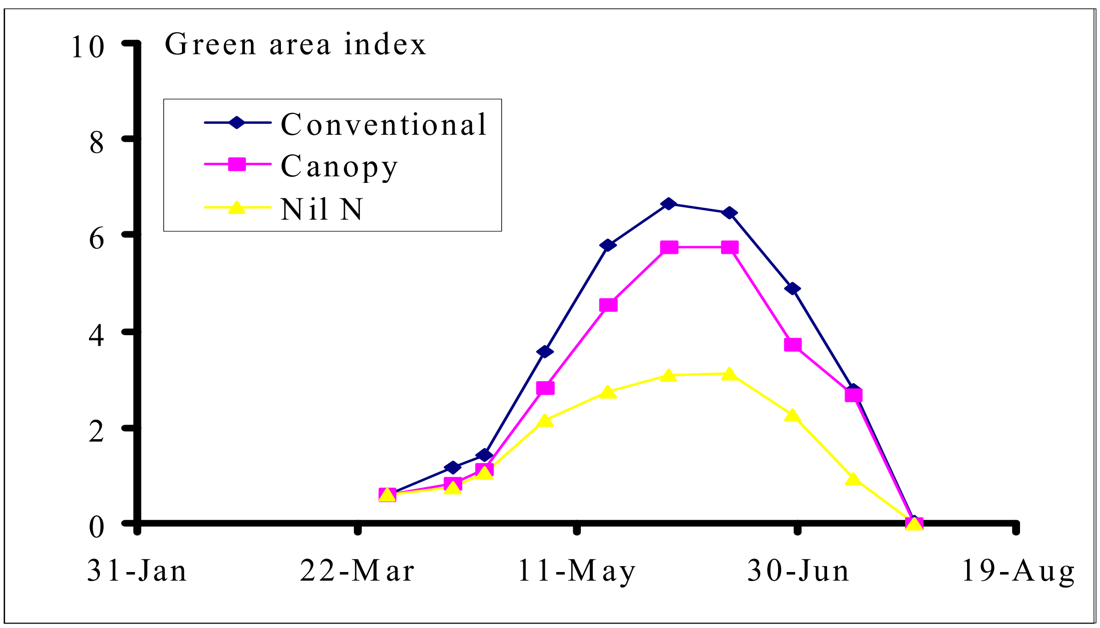
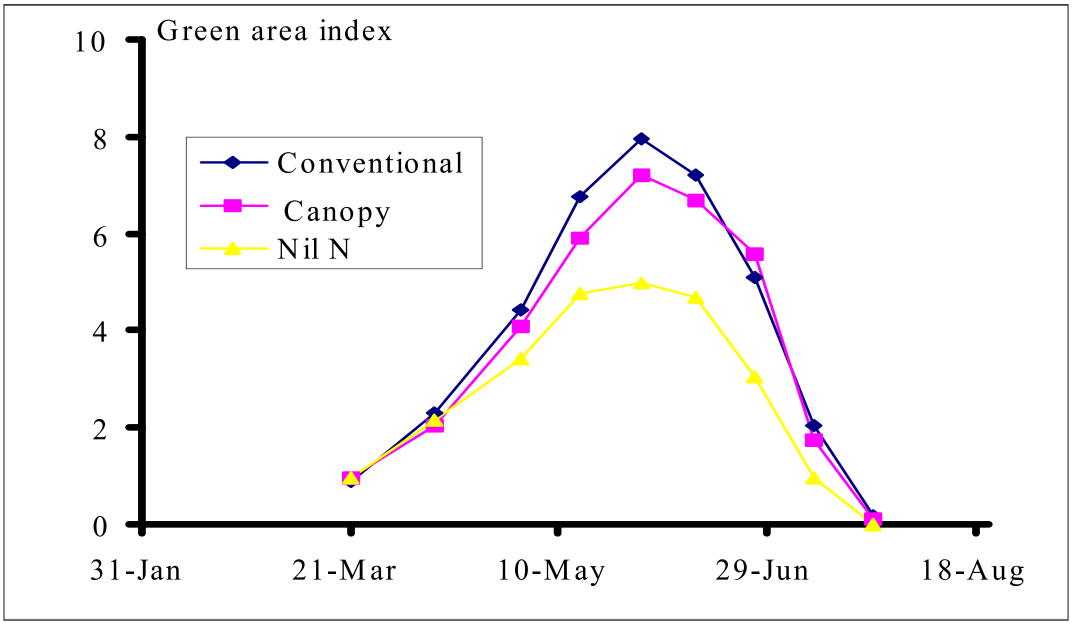


Figure 26 The effect of Conventional, Canopy and Nil fertiliser N applications to crops grown at University of Nottingham and ADAS Boxworth in 1994. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1995



ADAS Boxworth 1995

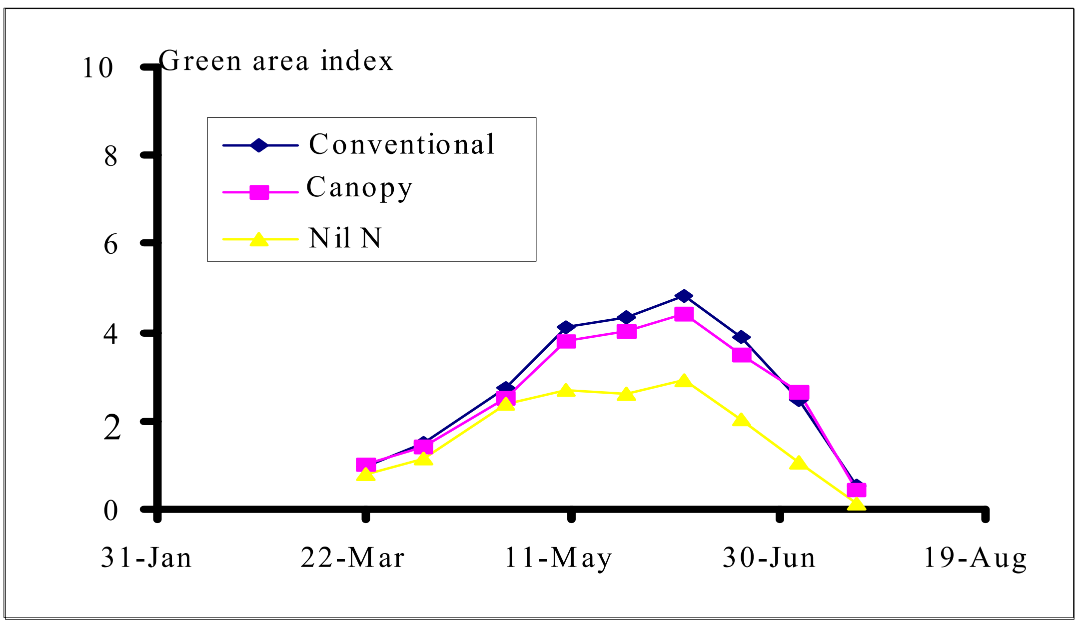
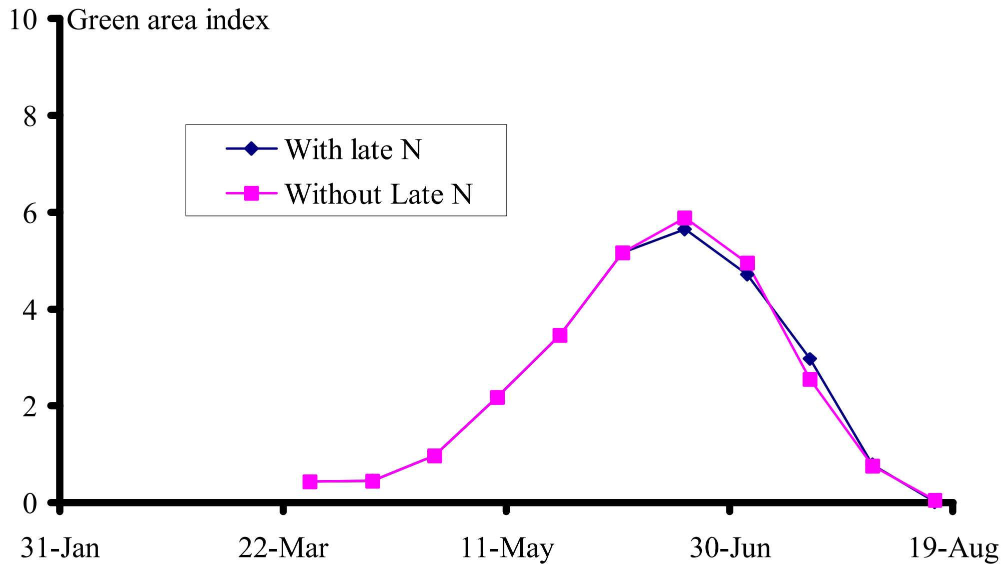


Figure 27 The effect of Conventional, Canopy and Nil fertiliser N applications to crops grown at University of Nottingham and ADAS Boxworth in 1995. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1994



ADAS Boxworth 1994

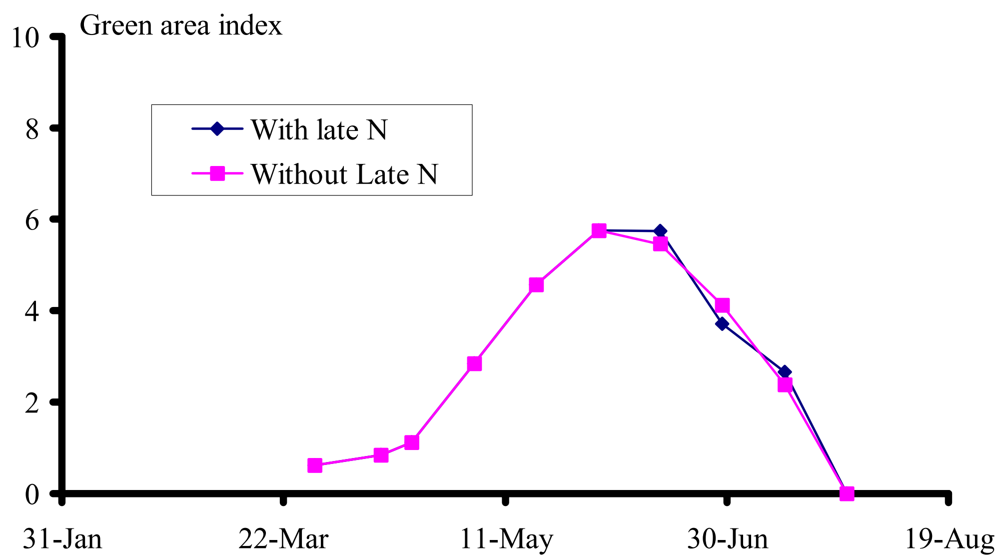
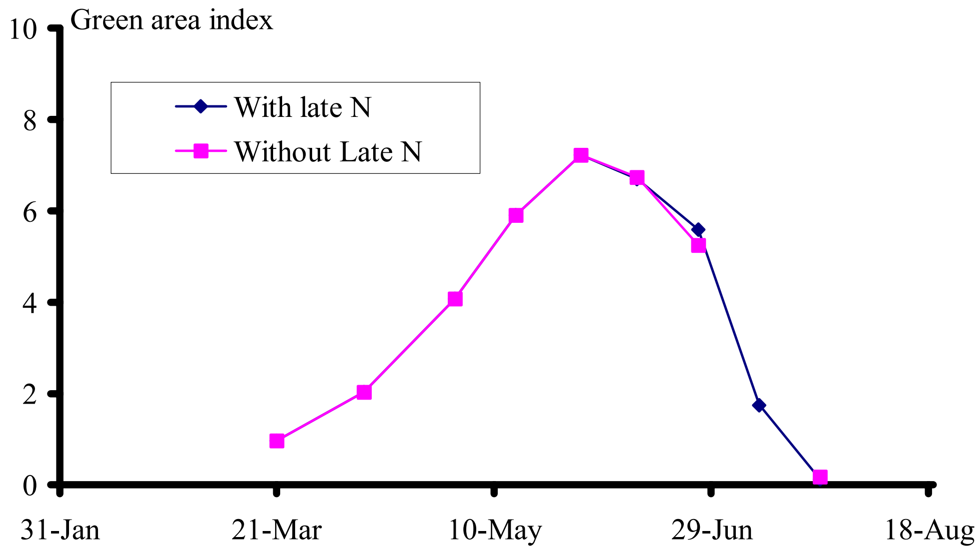


Figure 28 The effect of the late N applied at flowering on canopy size at the University of Nottingham and ADAS Boxworth in 1994. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1995



ADAS Boxworth 1995

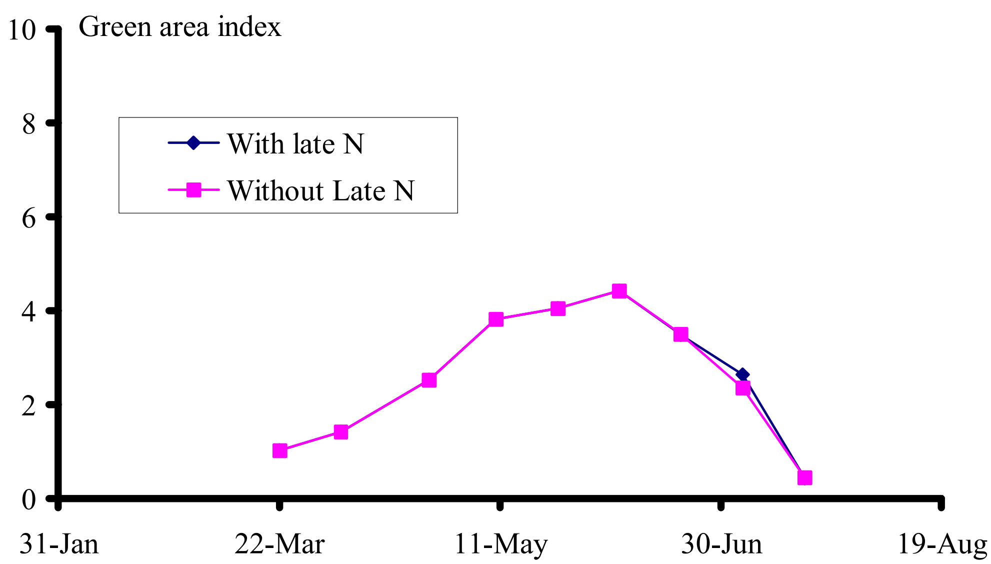


Figure 29 The effect of the late N applied at flowering on canopy size at the University of Nottingham and ADAS Boxworth in 1994. Data are expressed as means of sowing dates and N residues.

The preceding section on canopy expansion shows that the amount of N taken up by the crop is a good predictor of maximum canopy size and that the rules for managing canopy size restricted both overall maximum canopy size by 1 unit if GAI and reduced the variation in maximum canopy size. The effect of the late application of N at flowering did little to improve canopy duration.

It would appear that the Canopy Nitrogen Requirement for Mercia needs to be revised from 30 to 26 if GAI 5 is the target maximum canopy size. Furthermore, there needs to be examination of changes in Canopy Nitrogen Requirement between varieties because it appears from Project 0037/1/91 that the Canopy Nitrogen Requirement of Mercia is lower than most other current varieties.

Light interception

The Canopy Management approach for fertilising winter wheat relies upon understanding the relationship between canopy size and light interception. This relationship is Beer's Law. In the introduction to this report, it was argued that because incremental increases in canopy size result in successively smaller increases in the proportion of sunlight intercepted, there must be an optimum size of canopy beyond which further increases will be unlikely to result in an economic return from grain. Examination of the best data available together with estimates based on observation and experience, led us to suggest the optimum canopy size for wheat would be about GAI 5. This was set as the target maximum canopy size to achieve with the Canopy Management approach in the field tests. The key component of Beer's Law that has implications for the Canopy Management approach is k . This is the extinction coefficient and is a measure of the way the green surface intercepts light i.e. the flatter the green surface, the greater the proportion of light intercepted per unit of green area. Thus k is the part of the Beer's Law relationship which accounts for changes in canopy erectness or prostrateness. At the outset of this project, there was some uncertainty whether or not the use of N to control canopy size might adjust the way the green surface intercepts light i.e. the extinction coefficient (k). For example, if smaller canopies resulting from less N, had smaller leaves, they might be more vertical and thus a larger canopy would be required to intercept the requisite proportion of light.

The aim of this section is to examine, across the range of background crops in which the tests of Canopy Management was conducted, whether or not the relationship between green area index and the proportion of light intercepted conformed to Beer's Law. If this is found to be so, then Beer's Law provides a robust method to understand light interception in commercial crops of winter wheat. Firstly, the relationship between canopy size and light interception will be examined for the crops in the field tests of Canopy Management at the University of Nottingham and ADAS Boxworth and secondly, analyses will be presented of detailed measurements made at the University of Nottingham in 1994 which examined more closely the effects of N on canopy architecture and k.

Field tests of Canopy Management

For the crops grown at ADAS Boxworth and the University of Nottingham in all years, the proportion of light intercepted during the main part of the growing season was measured using tube solarimeters connected to a data logger. Canopy size was measured fortnightly following the procedures for growth analysis set out in the materials and methods of this report. When, over the duration of the main growing season, the proportion of light intercepted by a crop was related to its size at that time, the relationships always obeyed Beer's Law. This was not surprising because with this approach, the stage of crop development is confounded with change in size. Thus, canopy size is always small (and hence the proportion of light intercepted is always small) when measurements are made in spring (crops mainly leaf) and, when canopies were large during summer, the stem and ear contribute significantly to green area and canopy size and hence light interception is usually always large. Therefore, examination of Beer’s Law using data collected throughout the growing season is not a sufficiently good test with which to analyse for change in k. A more robust test is to examine the relationship between canopy size and light interception in crops of differing size but which are at the same stage of growth.

The effect of canopy size at both ear emergence and flowering on the proportion of light intercepted by all crops grown at ADAS Boxworth and the University of Nottingham is shown in Figure 30. Understanding canopy architecture at these times is important because at flag leaf emergence, canopy size is nearing maximum and stem reserves are being stored and, shortly after flowering, grain division begins followed by the onset of rapid grain filling. Therefore a shortfall in light interception due to inadequate canopy size at these times would be most critical and have significant implications for grain filling.

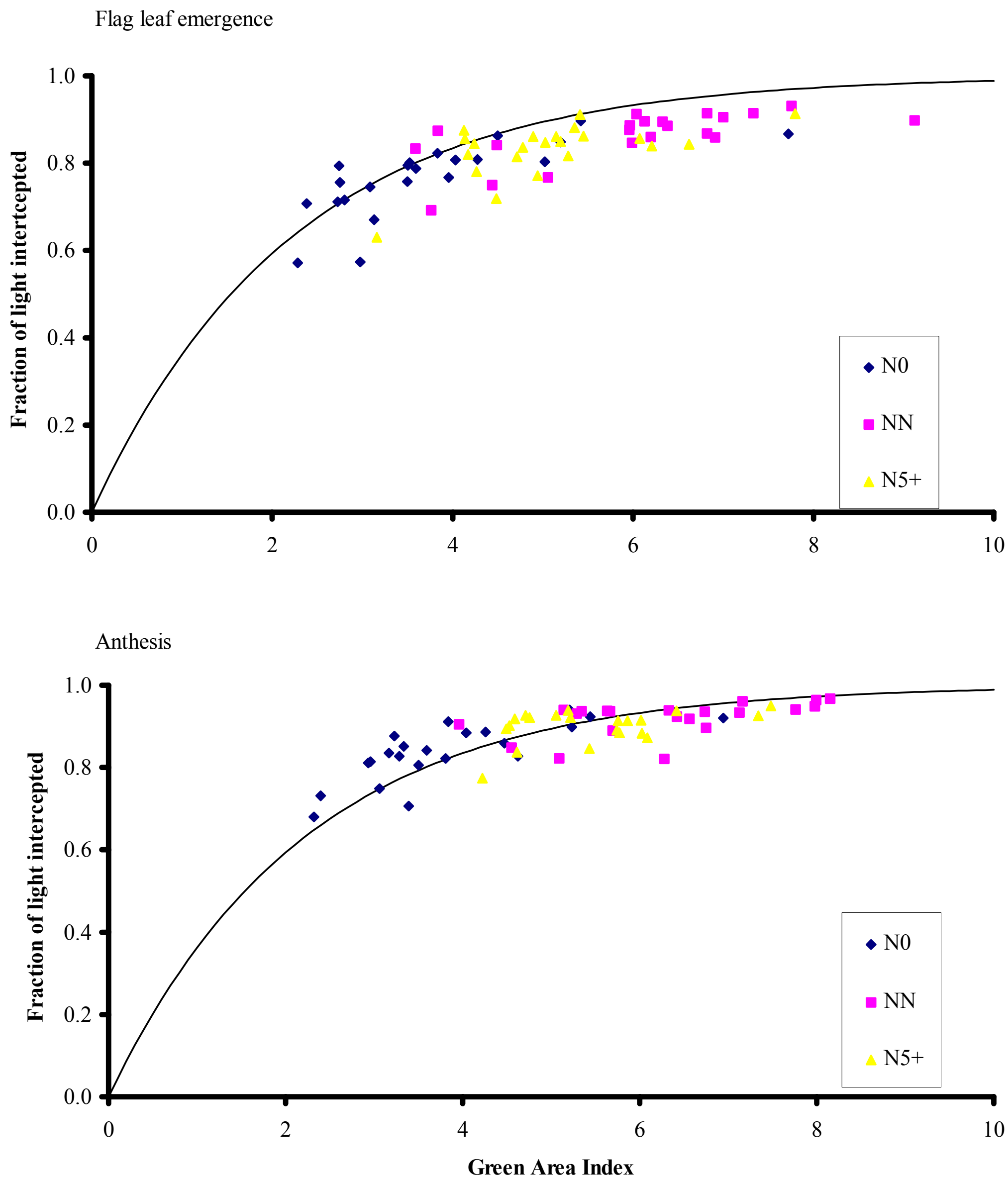


Figure 30 The effect of canopy size on the fraction of the incident sunlight intercepted by crops grown at ADAS Boxworth and the University of Nottingham in 1993, 1994 and 1995. The line is shown for comparison only and represents k = 0.45.

At GS 39 and GS 61, crops did not have canopies smaller than GAI 2.5 and therefore the curves are incomplete: most of the data form the flatter part of the curve. The absence of data points where GAI is less than 2.5 restricts the calculation of k from these data because it unsafe to extrapolate for canopies smaller than measured. To aid comparison, the curve is drawn setting k at 0.45. It is interesting that apart from the effects of N on canopy size, there is no clear separation of N treatments in the horizontal plane i.e. there was no consistent difference between N treatments in the way similar sized canopies intercepted light. This was so at both flag leaf emergence and flowering.

It is clear from the data in Figure 30 that crops never intercepted all the incident light; there was always a small proportion which filtered down through the canopy to the ground. This clearly shows the pointlessness of trying to intercept all the incident sunlight. It must be remembered however, that the relationships in Figure 30 are derived from measurements of total sunlight energy, only half of which can be used for photosynthesis. The unused half is dissipated by the crop and the energy used to drive transpiration. However, some of this light will always filter through the canopy to soil level. Therefore, the fraction of sunlight detected by solarimeters at the base of the crop will most likely be light energy outwith the spectrum which can be used for photosynthesis. Measurement of sunlight energy in the photosynthetically active part of the wavelength spectrum (PAR) can be determined using more sophisticated equipment (see later in section).

The relationship in Figure 30 was less variable when canopy size was large. This infers that influences on canopy architecture (that will affect k), will have larger implications where canopy size is more moderate. Also, canopies at flowering intercepted more light than canopies of equal size at flag leaf emergence, inferring canopy architecture had changed. This may however, have been the result of light interception by dead material or a change in erectness because as leaves age, they become less erect. Furthermore, ears are present at flowering and these might differ from leaves and stems in their ability to intercept sunlight.

Whilst at canopy sizes near GAI 5, there is some variation in the proportion of light intercepted, it seems clear from the data here that there is very little benefit in light interception from increasing canopy size above 6 GAI. However, when canopy size is less than GAI 6, it is important to examine for any effects of residual N, sowing date and spring N.

It is possible to gain some understanding of likely influences on k by calculating a value of k for each replicate field plot by assuming that all the canopy is required to intercept the measured proportion of light intercepted. This permits statistical analyses of influences on k by analysis of variance. Analyses of the overall effects of residual N, sowing date and spring N are presented in Table 29 for the crops grown in 1993, 1994 and 1995 at the University of Nottingham. Analyses have been restricted to this site because in the final year at ADAS Boxworth, very poor establishment in the late sowing restricted the measurements taken and thus the experimental design became unbalanced

There was no statistically significant difference in k between the conventionally fertilised and the Canopy Managed treatments. Thus it appears that use of N to moderate canopy size in Mercia is unlikely to have major influences on canopy architecture when canopy size is between 5 and 7 units of green area index. Surprisingly there was a consistent increase in k between GS 39 to GS 61. The precise reason for this is unclear. However, there are three possible causes. Firstly, after GS 39, the leaf canopy ages and increased laxness resulting from this ageing process would increase light interception per unit leaf area. Secondly, by GS 61 ears have emerged. The green area of ears was recorded as a projected area and no allowance was made for the complex arrangement of awns, lemmas and paleas, thus it is likely that the intercepting surface was underestimated. This would have the effect that more light would be intercepted than the 'apparent' green area would suggest and thus the estimate of k would be increased. Thirdly, dying leaves low down in the canopy intercept light but were not included with the green area measurement.

Table 29 Overall effects of residual N, sowing date and spring N treatment on canopy extinction coefficient (k) at the University of Nottingham. All data are averages over 1993, 1994 and 1995 seasons.

	Stage of Development	
	GS 39	GS 61
Overall effect of Residual N		
High	0.39	0.49
Low	0.41	0.47
Overall effect of sowing date		
Early	0.38	0.46
Late	0.42	0.50
Overall effect of spring N		
Nil	0.43	0.51
Conventional	0.38	0.46
Canopy	0.39	0.47

The field tests of Canopy Management clearly showed there was little benefit to light interception from increasing canopy size above 6 GAI and that sowing date and spring N treatment can have small but significant effects on canopy architecture. However, these measurements are based on analyses of the interception of light in the total spectrum by the canopy as a whole and take no account of the mechanisms of light penetration layer by layer down to ground. Such detailed measurements are necessarily time consuming and could not be conducted within the field tests. However, Mark Everett and Mark Dodds, two students at the University of Nottingham in 1994, made detailed measurements of light penetration into the unfertilised and conventionally fertilised early sown crops on the low N residue. The results from this study are presented to help clarify the findings reported above.

Detailed measurement of extinction coefficient at University of Nottingham

From late May through to early July in 1994, detailed measurements of canopy structure were made in unfertilised and conventionally fertilised crops sown early on the low N residue (LNES). These measurements differed from those used in the section above in three critical respects. Firstly, canopies were stratified into 10cm layers from the top of the crop down to soil level. This allows analysis of distribution of light within the canopy rather than measuring interception by the canopy as a whole and permits analysis of possible changes in k with depth in the canopy. Secondly, the light intercepted by each of the layers was measured using a ceptometer which only records light in the PAR part of the light spectrum and therefore provides a more accurate analysis of distribution of the light used for photosynthesis. Thirdly, areas of non-green crop structures were recorded in each layer to examine whether or not their inclusion in the estimates of canopy size altered the value of k.

Samples for growth analysis were taken from the Nil N and conventionally fertilised crops on seven occasions between 25 May and 4 July when canopy size varied from 4 to 7 GAI. Figure 31 shows the proportion of PAR intercepted by total canopy on each sampling occasion. As found within the field tests of Canopy Management, there were no small canopies: canopies were larger than GAI 4. The Beer's Law relationship was therefore incomplete and extrapolation of the relationship to crops with less than 4 GAI would be inaccurate. However, for comparison with the data from the field tests the curve drawn represents a crop with k at 0.45.

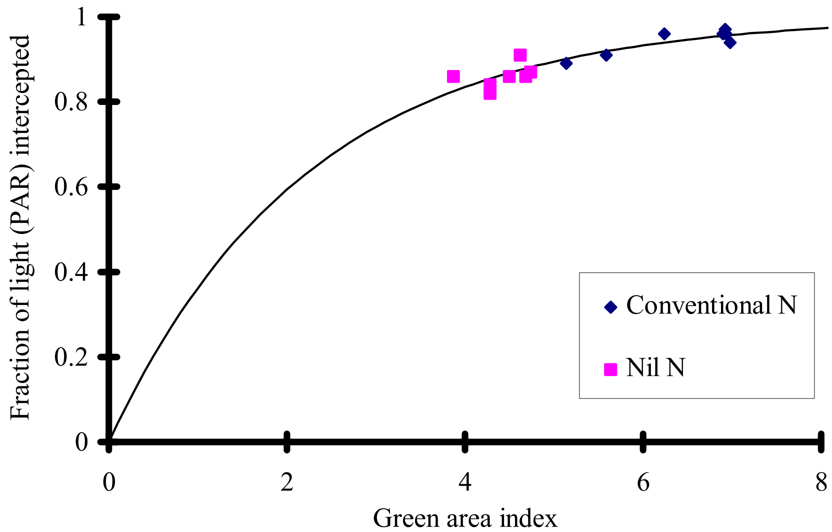


Figure 31 The relationship between canopy size and the proportion of PAR intercepted by unfertilised and conventionally fertilised crops at the University of Nottingham in 1994. The curve is drawn assuming k = 0.45 to give comparison with data from the field tests.

The data in Figure 31 show that these crops never intercepted 100% of the incident PAR. However, at when canopies were about 6 GAI, PAR interception was about 95% whereas in the field tests, crops with GAI 6 intercepted 80% and 90% of the total light at GS 39 and GS 61 respectively. The curve in Figure 31 is drawn for comparison with those in Figure 30, setting k at 0.45. The data in Figure 31 lie close to the line inferring that 0.45 must be a very close approximation describing the interception of PAR by whole canopies of wheat. Although this supports the inference from the field tests that k for whole crops is likely to be close to 0.45, further analysis is required to examine the distribution of PAR through the crop canopy. This is necessary to investigate whether or not k might change with depth in the canopy and to examine whether measures of whole canopy green area index provide reliable estimates of k. The very time consuming nature of the stratified measurements of canopy architecture restricted analysis of replicated field plots to one sample occasion on 23 June. These data are therefore the most accurate available and further analyses will be restricted to this sample date.

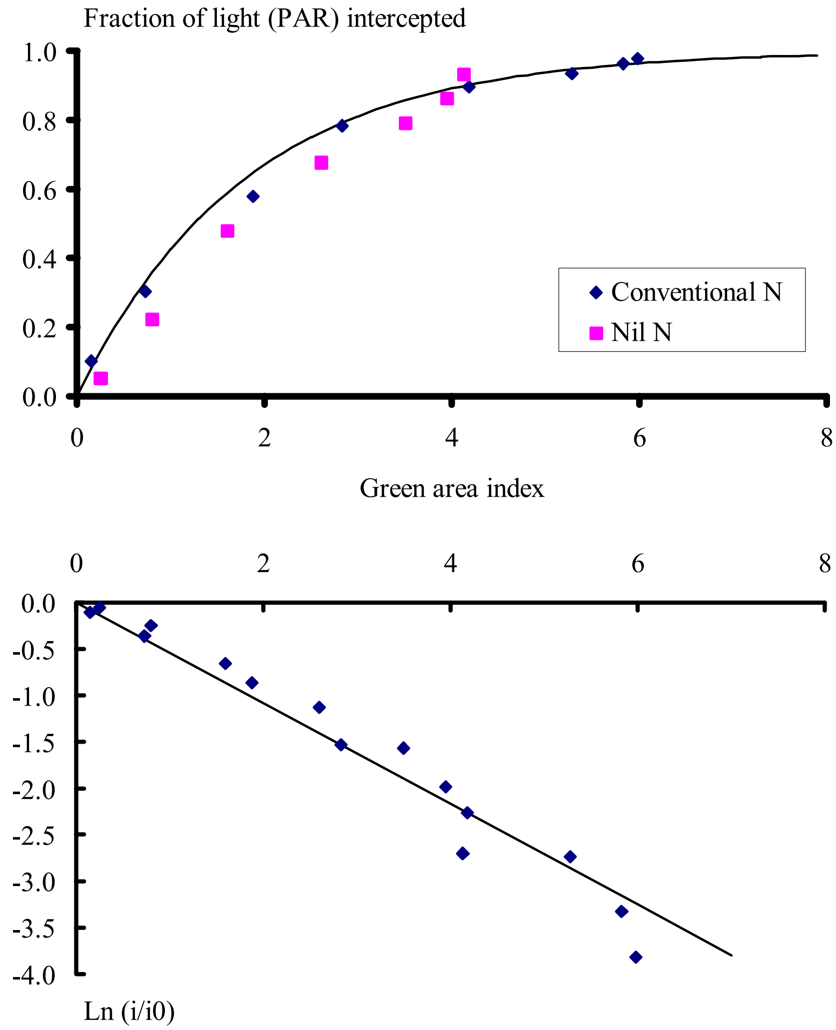


Figure 32 Relation between green area index accumulated in stratified layers from top of canopy downwards and the proportion of light (PAR) intercepted in the unfertilised and conventionally fertilised crops at the University of Nottingham in 1994. The curve is fitted using the value of k (0.56) derived from linear regression in the lower graph.

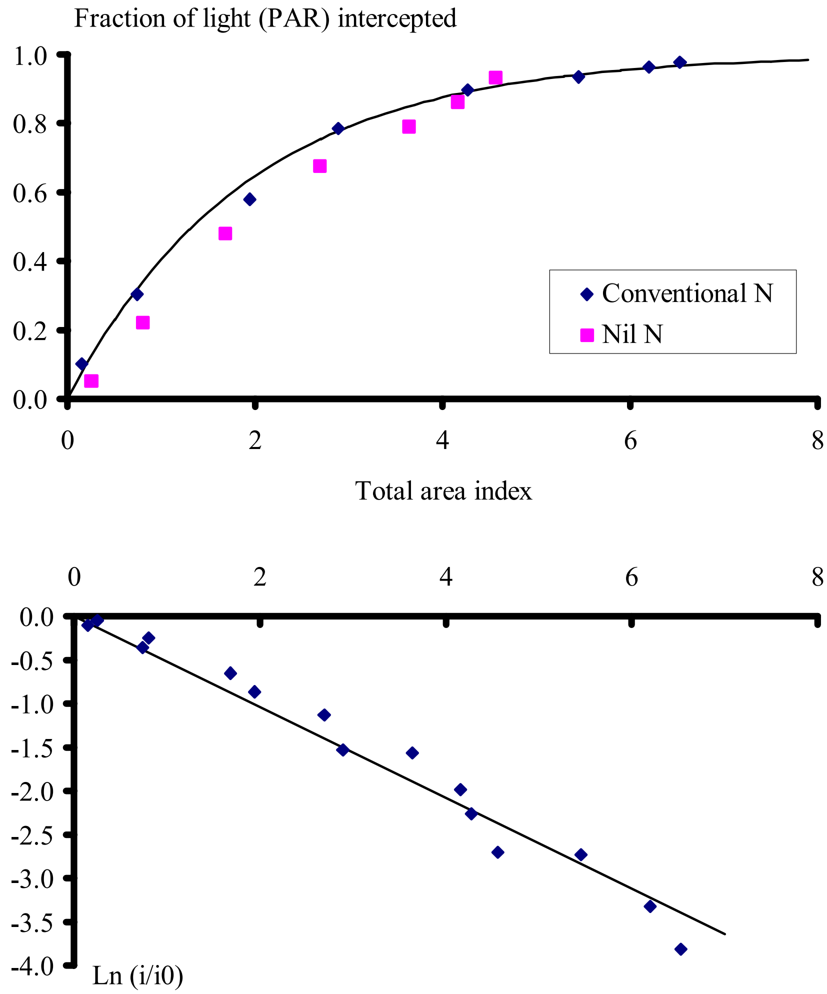


Figure 33 Relation between *total* area index accumulated in stratified layers from top of canopy downwards and the proportion of light (PAR) intercepted in the unfertilised and conventionally fertilised crops at the University of Nottingham in 1994. The curve is fitted using the value of k (0.52) derived from linear regression in the lower graph.

The relationship between canopy size and the proportion of PAR intercepted by the two crops on the 23 June is shown in Figure 32. The estimate of k, based on linear regression through a plot of green area index against ln(i/io), was 0.56. This was highly significant and accounted for over 95% of the variation in light interception. However, there was a trend for the relationship to deviate from a straight line at lower depths in the canopies. This was considered to be caused by senescing material intercepting light and to adjust for this, Beer's Law was plotted and k was recalculated using total area index which included the area of any non-green components (Figure 33). This correction improved the linear fit but resulted in only a small change in k to 0.52. It is expected that such corrections would have greater implications later during them season when more of the canopy was senescing.

In both Figure 32 and Figure 33, the data collected from the unfertilised crop appears to lie slightly below the line. Calculation of k for each of the crops showed k to be smaller 0.52 vs 0.57 although they were not significantly different. The slightly lower k for the unfertilised crop is at variance with the inference from the field tests, however, the estimate using PAR is most likely to be representative of interception of light used for photosynthesis and is commensurate with the observation that unfertilised crops tend to have more erect leaves and the paler green leaves would likely be more opaque to total light than PAR.
Our observations lead us to suggest that during the early phase of grain filling, k in Mercia is likely to be between 0.45 and 0.5 for total light and will be between 0.5 and 0.55 for PAR. The results here, demonstrate that Beer's Law holds within Mercia wheat grown over a wide range of conditions and there is clearly little benefit to light interception to be gained from increasing canopy size above 6 GAI. Furthermore, they indicate that the value of k used in the introduction for calculation of the optimum GAI (0.6) was perhaps a slight overestimate. However, having demonstrated that the principle of Beer's Law applies, it will be necessary to undertake more detailed measurements than was possible in this study to understand light interception in canopies during late grain filling where there is a large proportion of dead material.

Biomass production -

The underlying assumption of Canopy Management is that light interception by wheat canopies can be optimised by limiting canopy expansion to that sufficient to just capture the prescribed proportion of incident sunlight. The previous section considered the effect of fertiliser N on both canopy size and architecture, good support was found to uphold Beer's Law as a method of linking canopy size to light interception. The next step in the framework linking fertiliser application to wheat yield is examine how the captured energy from sunlight is converted into biomass i.e. crop dry weight and hence growth.

The general pattern of biomass production is shown in Figure 34 for an early sown crop grown where soil N residues were small at the University of Nottingham in 1993. These crops received Conventional, Canopy Management or Nil fertiliser applications of N. This pattern was typical of that found in all the tests of Canopy Management. Crop dry matter was small in early spring; limited by cold temperatures and low levels of incident sunlight energy (usually less than 5 $MJ/m^2/day$) compounded with small canopies with low fractional interception. During late April / early May, the increase in crop dry matter was rapid, often increasing linearly until mid July after which, dry matter was either stable or fell slightly in the two weeks prior to harvest.

In order to investigate how dry matter production in wheat is controlled, it is necessary to investigate how the general pattern of growth is modified by fertiliser N against the changes imposed by season, site, sowing date and soil N residue. The overall effects of fertiliser N on dry matter accumulation are presented as means of sowing dates and soil N residues for the crops grown at the University of Nottingham and ADAS Boxworth in all three years of the Canopy Management tests. The main influence of sowing date and soil N residue will then be presented where effects were largest i.e. at the University of Nottingham in 1994 and 1995 respectively.

At the University of Nottingham in 1993, maximum crop dry matter was about 16 t/ha and overall, there was no significant difference between Conventional and Canopy Management applications (Figure 35). Unfertilised crops produced, on average, 3 t/ha less dry matter at maximum. After maximum, crop dry matter remained constant from mid July until harvest in mid August. At ADAS Boxworth in this year, Conventional applications of N resulted in 20 t/ha of dry matter at maximum but this fell by about 2 t/ha by harvest. At ADAS Boxworth, from the onset of rapid dry matter accumulation through to harvest, the crops receiving Canopy Management always had slightly less dry matter. The unfertilised crops had a similar pattern of growth but reached a maximum of about 16 t/ha, about 3 t/ha more than unfertilised crops at the University of Nottingham.

In 1994, the average maximum amounts of dry matter produced at the University of Nottingham and ADAS Boxworth were similar to those in 1993 (Figure 36). Generally, less crop dry matter was lost prior to harvest at the University of Nottingham.

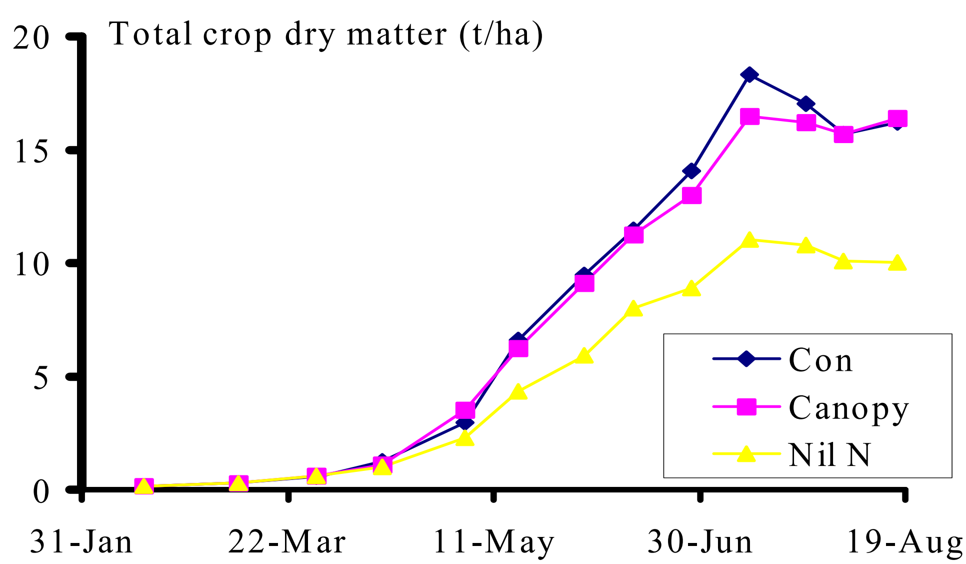
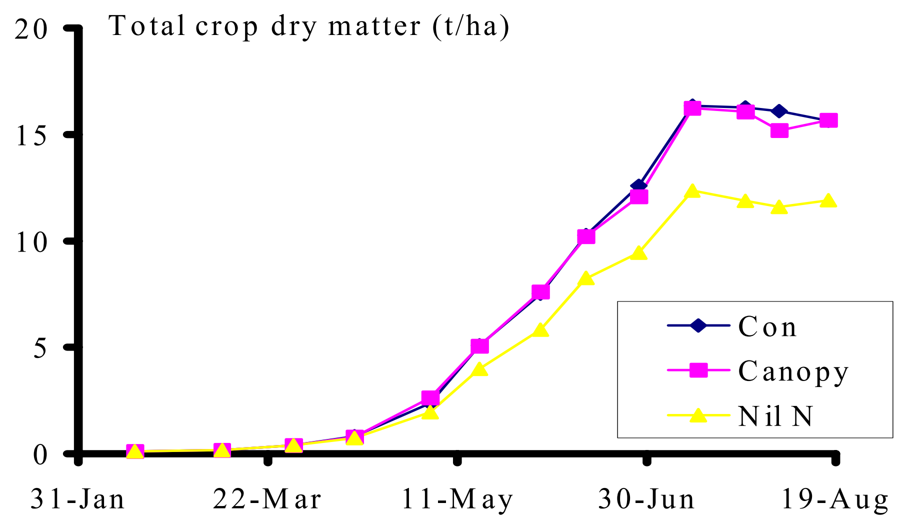


Figure 34 Pattern of dry matter accumulation at the University of Nottingham in 1993 in crops receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. Crops were sown early into soils with low N residues.

University of Nottingham



ADAS Boxworth

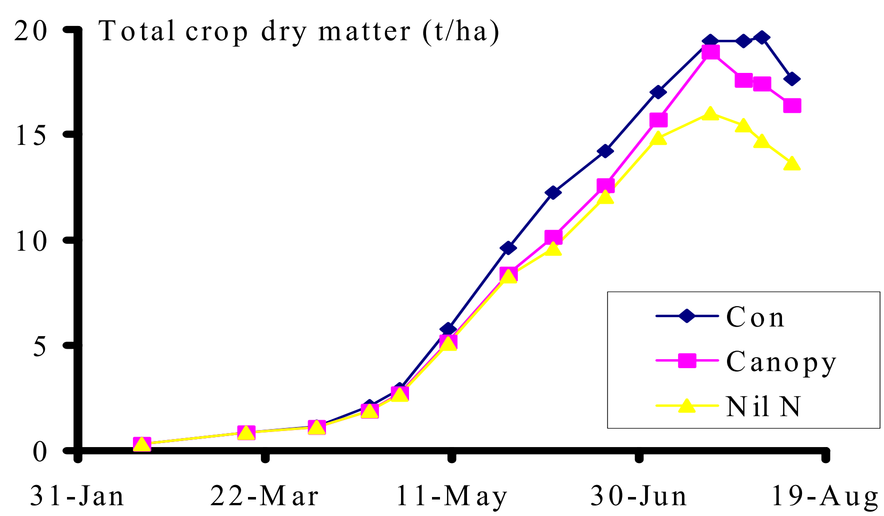
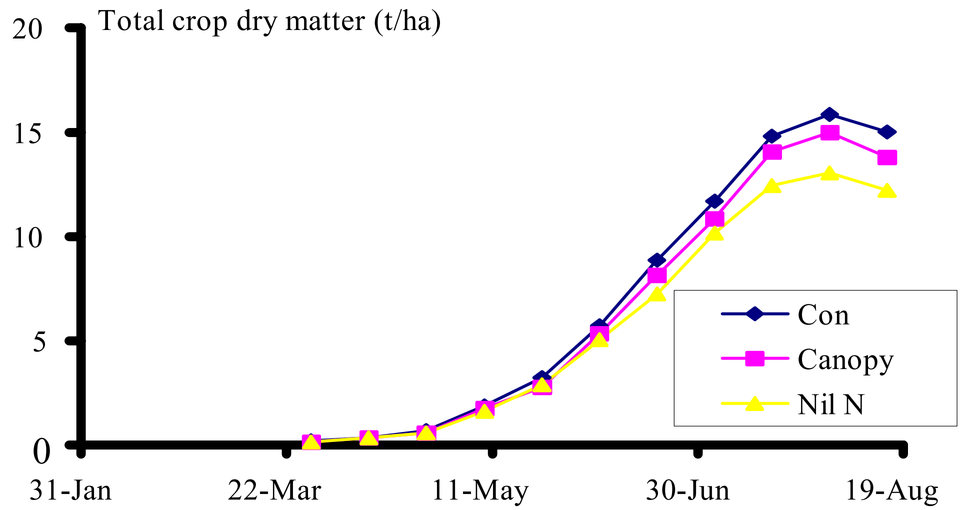


Figure 35 Accumulation of dry matter at the University of Nottingham and ADAS Boxworth in 1993 following conventional (Con), Canopy Management (Canopy) and nil fertiliser N applications. Data are expressed as means of sowing dates and N residues.

University of Nottingham



ADAS Boxworth

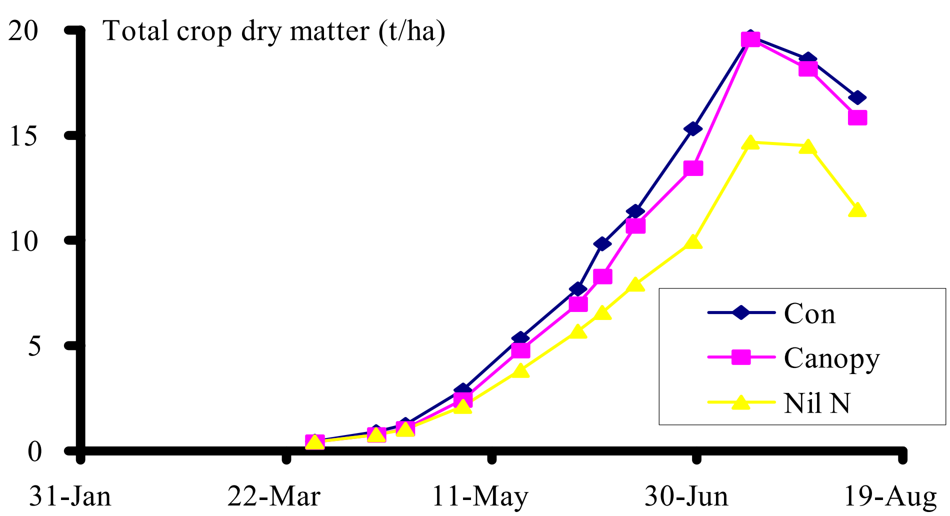


Figure 36 Accumulation of dry matter at the University of Nottingham and ADAS Boxworth in 1994 following conventional (Con), Canopy Management (Canopy) and nil fertiliser N applications. Data are expressed as means of sowing dates and N residues.

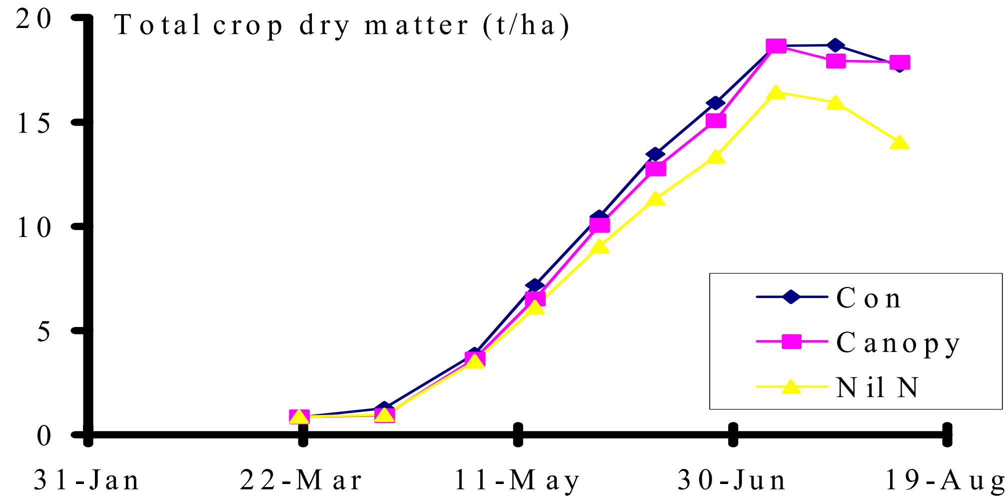
In 1995, the pattern of dry matter accumulation at the University of Nottingham and ADAS Boxworth was reversed; maximal amounts were larger at the University of Nottingham whilst at ADAS Boxworth, less maximum dry matter resulted from a slower rate of accumulation (Figure 37). The loss of dry matter at ADAS Boxworth in 1993 and 1994 which appeared to be associated with the production of larger amounts of dry matter, occurred again despite maximal dry matter being only 15 t/ha in fertilised crops and about 9 t/ha in unfertilised crops.

The effect of sowing date was most pronounced at the University of Nottingham in 1994 where late sowing was delayed until early March (Figure 38). In the early sowings, the onset of rapid accumulation of dry matter began in late April but in the late sowings this was delayed until mid May. The rate of growth in both sowings appeared very similar and hence less dry matter was accumulated in the late sowings because the duration of growth was curtailed as the crops developed more rapidly. The difference between fertilised and unfertilised crops was larger in the early sowings indicting that canopy duration has implications for biomass production.

The effects of soil N residue on crop growth were largest at the University of Nottingham in 1995. Here, there was on average no difference in dry matter accumulation between fertilised crops and unfertilised crops showing that where soil N residue are large, they can provide for crop growth not restricted by N (Figure 39). Where soil N residues were smaller, there was a greater response from fertiliser N; the smaller amount of dry matter in unfertilised crops in mid July was generally the result of a reduction in the rate of accumulation and not a shorter duration of growth.

These general descriptions of crop growth indicate several important features. Firstly, N exerted a major influence on the maximum amount of dry matter produced by largely reducing the rate of accumulation; the duration of growth appeared to be little affected. However, the sampling interval used in this study (two weeks) was probably too long to detect any small changes. Secondly, there was commonly a loss of biomass between maximum and final harvest which, in some cases was over 2 t/ha and, tended to be larger at ADAS Boxworth than at the University of Nottingham.

University of Nottingham



ADAS Boxworth

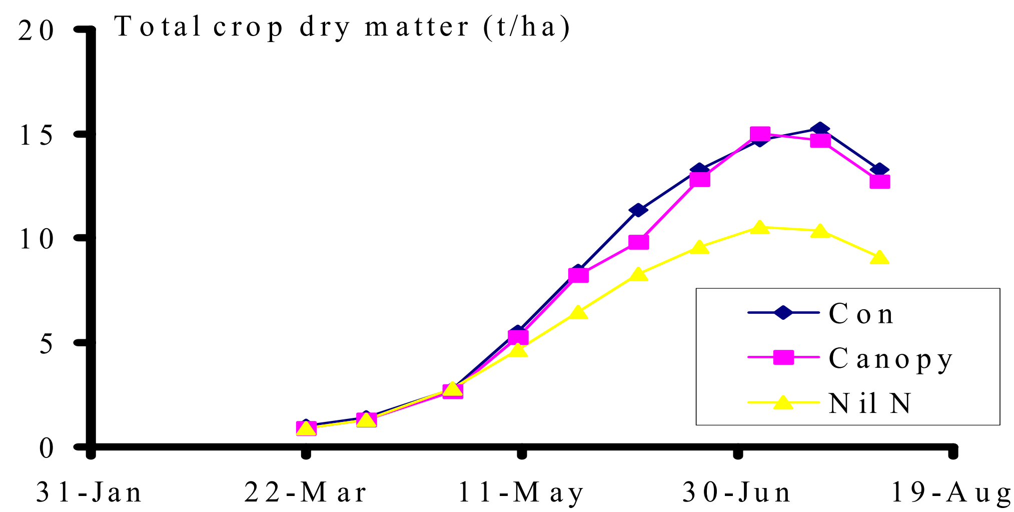
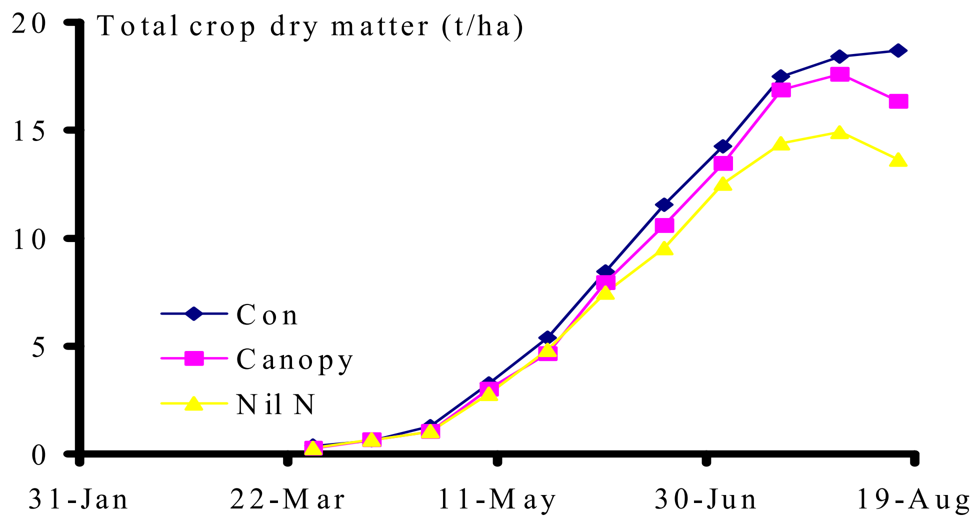


Figure 37 Accumulation of dry matter at the University of Nottingham and ADAS Boxworth in 1995 following conventional (Con), Canopy Management (Canopy) and nil fertiliser N applications. Data are expressed as means of sowing dates and N residues.

University of Nottingham 1994, early sowings



University of Nottingham 1994, late sowings

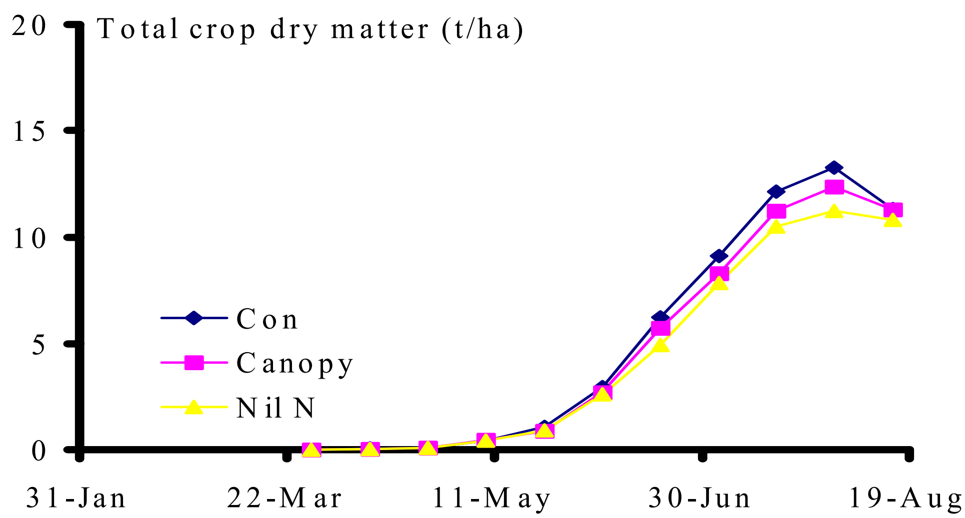
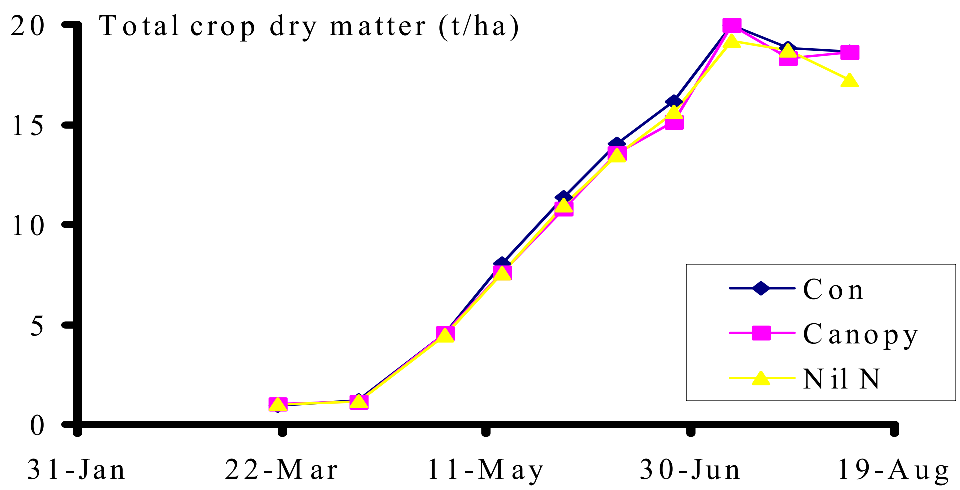


Figure 38 The effect of sowing early or late on dry matter accumulation following conventional (Con), Canopy Management (Canopy) and nil fertiliser N applications at the University of Nottingham in 1994. Data are expressed as means of N residues.

University of Nottingham 1995, high N residues



University of Nottingham 1995, low N residues

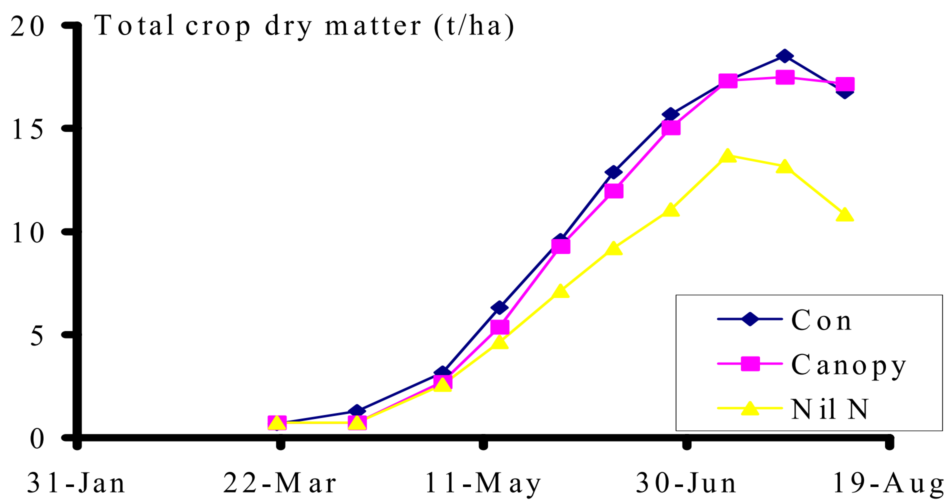


Figure 39 The effect of soil N residue on dry matter accumulation production following conventional (Con), Canopy Management (Canopy) and nil fertiliser N applications at the University of Nottingham in 1995. Data are expressed as means of sowing dates.

The effects of nitrogen and other treatments on maximum dry matter, the rate of crop growth, dry matter at harvest and the loss of dry matter in the lead up to harvest for the individual test crops are summarised in the following Tables. In 1993 (Table 30) , unfertilised crops always produced least maximal dry matter and the amount was not affected by late sowing. In seven of the eight test crops, Canopy Management resulted in less biomass at maximum but unlike the unfertilised crops, late sowing reduced maximal biomass by on average 1 to 2 t/ha. The rate of dry matter accumulation was always least in unfertilised crops and was relatively unaffected by soil N residue but was increased from 0.14 t/ha/day to 0.17 t/ha/day by late sowing. The rates of growth of the fertilised crops averaged about 0.2 t/ha/day and were less variable than in unfertilised crops and, less affected by change in site, sowing date and soil N residue. The loss of dry matter between maximal dry matter and harvest was consistently larger at ADAS Boxworth, averaging 3.26 t/ha compared with 0.85 t/ha at the University of Nottingham. There appeared to be no consistent effect of fertiliser N on these pre harvest losses.

In 1994 (Table 31), late sowing at the University of Nottingham reduced maximum dry matter more in fertilised than unfertilised crops. This was associated with a reduction in the rate of growth from about 0.2 t/ha/day down to 0.16 t/ha/day. And, despite the smaller amount of dry matter, there were still significant losses of dry matter before harvest. At ADAS Boxworth, Conventional and Canopy Management applications of N resulted in similar maximal amounts of dry matter which were consistently larger than in unfertilised crops because the latter grew at slower rates. Significant losses of dry matter occurred prior to harvest from both fertilised and unfertilised crops. These losses were larger at ADAS Boxworth than at the University of Nottingham.

In 1995 (Table 32), unfertilised crops sown early into soil with high residues of soil N produced the same maximal dry matter as crops receiving Conventional, Canopy Management applications of N. Unfertilised crops sown either early or late into soils with small N residues produced 5t/ha less dry matter at maximum than conventionally fertilised crops. The rates of growth reflected maximal dry matter, again showing that crops supplied with larger amounts of N grew more rapidly. There was no consistent pattern between treatments in the loss of dry matter in the lead up to harvest however, losses tended to be slightly larger in earlier sowings.

At ADAS Boxworth in 1995 (Table 32), Canopy Management produced more dry matter at maximum than the conventional applications of N and unfertilised crops produced less dry matter than fertilised crops because of a slower rate of dry matter accumulation.

Over all sites and seasons (Table 33), fertilised crops produced 3-4t/ha more dry matter at maximum than unfertilised crops. However, this was less where unfertilised crops were grown on soils with high N residues. Canopy Management reduced maximal dry matter by about 0.6 t/ha compared with Conventional applications of N. This was consistent over the three seasons and appeared to be unaffected by sowing date and soil N residue. The rate of dry matter accumulation during rapid growth was similar between Conventional and Canopy management applications. Unfertilised crops had the lowest rates of growth which were smallest where soil N residues were small. Differences between nitrogen treatments in dry matter at harvest were similar to those at maximum dry matter because overall losses between maximum dry matter and harvest were similar. On average, both fertilised crops and unfertilised crops lost about 1.8 t/ha between maximum dry matter and harvest. These losses were larger in early sowings and much larger at ADAS Boxworth than at the University of Nottingham.

Table 30 The effect of conventional (Con), Canopy Management (Canopy) and nil fertiliser N applied to each of the test crops at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993 on maximum crop dry matter, rate of growth, crop dry matter at harvest and loss of dry matter between maximum and harvest.

Site	Test crop	Maximum dry matter (t/ha)			Rate of growth (t/ha/day dwt)			Dry matter at harvest (t/ha)			Loss of dry matter (t/ha)		
		Con	*Canopy*	*Nil*	*Con*	*Canopy*	*Nil*	*Con*	*Canopy*	*Nil*	*Con*	*Canopy*	*Nil*
UN 1993	*HNES*	17.94	17.76	13.40	0.19	0.21	0.15	16.48	16.01	14.62	1.46	1.75	-1.22
UN 1993	*HNLS*	15.11	15.49	12.90	0.18	0.19	0.16	13.83	15.57	12.22	1.28	-0.08	0.68
UN 1993	*LNES*	18.29	16.48	10.80	0.22	0.19	0.13	16.20	16.37	10.02	2.09	0.11	0.78
UN 1993	*LNLS*	16.40	16.08	12.36	0.21	0.21	0.16	16.05	14.81	10.86	0.35	1.27	1.50
BX 1993	*HNES*	20.05	20.92	17.30	0.19	0.21	0.16	18.25	16.62	15.25	1.80	4.30	2.05
BX 1993	*HNLS*	19.24	18.94	16.95	0.21	0.20	0.18	16.81	16.36	14.40	2.43	2.58	2.55
BX 1993	*LNES*	20.61	17.88	14.49	0.20	0.17	0.13	19.22	16.59	12.40	1.39	1.29	2.09
BX 1993	*LNLS*	19.20	18.01	16.02	0.19	0.19	0.17	16.23	15.94	12.52	2.97	2.07	3.50
Means	UN	16.94	16.45	12.37	0.20	0.20	0.15	15.64	15.69	11.93	1.30	0.76	0.44
Means	BX	19.78	18.94	16.19	0.20	0.19	0.16	17.63	16.38	13.64	2.15	2.56	2.55
Means	Early sown	19.22	18.26	14.00	0.20	0.20	0.14	17.54	16.40	13.07	1.69	1.86	0.93
Means	Late sown	17.49	17.13	14.56	0.20	0.20	0.17	15.73	15.67	12.50	1.76	1.46	2.06
Means	High N Res.	18.09	18.28	15.14	0.19	0.20	0.16	16.34	16.14	14.12	1.74	2.14	1.02
Means	Low N Res.	18.63	17.11	13.42	0.21	0.19	0.15	16.93	15.93	11.45	1.70	1.19	1.97

Table 31 The effect of conventional (Con), Canopy Management (Canopy) and nil fertiliser N applied to each of the test crops at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1994 on maximum crop dry matter, rate of growth, crop dry matter at harvest and loss of dry matter between maximum and harvest.

Site	**Test crop**	**Maximum dry matter (t/ha)**			**Rate of growth (t/ha/day dwt)**			**Dry matter at harvest (t/ha)**			**Loss of dry matter (t/ha)**		
		Con	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***
UN 1994	*HNES*	18.15	17.24	14.93	0.20	0.20	0.17	17.18	16.50	14.48	0.97	0.70	0.45
UN 1994	*HNLS*	13.76	10.74	11.22	0.16	0.15	0.15	10.88	10.84	10.85	2.88	-0.10	0.37
UN 1994	*LNES*	20.19	17.96	14.89	0.21	0.20	0.16	20.19	16.19	12.78	0.00	1.77	2.11
UN 1994	*LNLS*	12.77	13.37	11.22	0.17	0.16	0.14	11.76	11.72	10.75	1.01	1.65	0.47
BX 1994	*HNES*	21.71	19.86	16.76	0.26	0.24	0.20	17.35	15.92	12.72	4.36	3.94	4.04
BX 1994	*HNLS*	18.01	18.96	14.54	0.22	0.25	0.18	16.02	15.23	11.98	1.99	3.73	2.56
BX 1994	*LNES*	18.38	18.94	13.73	0.21	0.26	0.16	17.03	16.66	10.15	1.35	2.28	3.58
BX 1994	*LNLS*	20.63	18.43	13.85	0.26	0.23	0.18	16.82	15.29	11.00	3.81	2.84	2.85
Means	UN	16.22	14.83	13.07	0.19	0.18	0.16	15.00	13.81	12.22	1.22	1.02	0.85
Means	BX	19.68	19.05	14.72	0.24	0.25	0.18	16.81	15.85	11.46	2.88	3.20	3.26
Means	Early sown	19.61	18.50	15.08	0.22	0.23	0.17	17.94	16.32	12.53	1.67	2.18	2.55
Means	Late sown	16.29	15.38	12.71	0.20	0.20	0.16	13.87	13.35	11.15	2.42	2.03	1.56
Means	High N Res.	17.91	16.70	14.36	0.21	0.21	0.18	15.36	14.62	12.51	2.55	2.08	1.86
Means	Low N Res.	17.99	17.18	13.42	0.21	0.21	0.16	16.45	15.04	11.17	1.54	2.14	2.25

Table 32 The effect of conventional (Con), Canopy Management (Canopy) and nil fertiliser applied to each of the test crops at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1995 on maximum crop dry matter, rate of growth, crop dry matter at harvest and loss of dry matter between maximum and harvest.

Site	Test crop	Maximum dry matter (t/ha)			Rate of growth (t/ha/day dwt)			Dry matter at harvest (t/ha)			Loss of dry matter (t/ha)		
		Con	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***
UN 1995	*HNES*	21.52	20.79	21.23	0.22	0.21	0.22	19.07	19.13	18.15	2.45	1.696	3.08
UN 1995	*HNLS*	18.41	19.15	17.09	0.17	0.20	0.18	18.21	18.11	16.34	0.20	1.04	0.75
UN 1995	*LNES*	19.71	18.30	14.55	0.18	0.18	0.15	17.08	17.57	10.77	2.63	0.73	3.78
UN 1995	*LNLS*	17.34	17.92	12.97	0.17	0.18	0.14	16.46	16.71	10.91	0.88	1.21	2.06
BX 1995	*HNES*	15.11	16.86	12.11	0.17	0.19	0.12	13.02	13.36	9.97	2.09	3.50	2.14
BX 1995	*LNES*	16.45	14.04	9.12	0.16	0.16	0.09	13.52	12.04	8.20	2.93	2.00	0.92
Means	UN	19.25	19.04	16.46	0.19	0.19	0.17	17.71	17.88	14.04	1.54	1.16	2.42
Means	BX	15.78	15.45	10.62	0.17	0.18	0.11	13.27	12.70	9.09	2.51	2.75	1.53
Means	Early sown	18.20	17.50	14.25	0.18	0.19	0.15	15.67	15.53	11.77	2.53	1.97	2.48
Means	Late sown	17.88	18.54	15.03	0.17	0.19	0.16	17.34	17.41	13.63	0.54	1.13	1.41
Means	High N Res.	18.35	18.93	16.81	0.19	0.20	0.17	16.77	16.87	14.82	1.58	2.07	1.99
Means	Low N Res.	17.83	16.75	12.21	0.17	0.17	0.13	15.69	15.44	9.96	2.15	1.31	2.25

Table 33 The overall effect of conventional (Con), Canopy Management (Canopy) and nil fertiliser N applied to each of the test crops at the University of Nottingham (UN) and ADAS Boxworth (AB) on maximum crop dry matter, rate of growth, crop dry matter at harvest and loss of dry matter between maximum and harvest.

Overall	**Maximum dry matter (t/ha)**			**Rate of growth (t/ha/day dwt)**			**Dry matter at harvest (t/ha)**			**Loss of dry matter (t/ha)**		
Means	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***	***Con***	***Canopy***	***Nil***
Grand mean	18.14	17.46	14.20	0.20	0.20	0.16	16.26	15.63	12.33	1.88	1.83	1.87
1993	18.36	17.70	14.28	0.20	0.20	0.16	16.63	16.03	12.79	1.72	1.66	1.49
1994	17.95	16.94	13.89	0.21	0.21	0.17	15.90	14.83	11.84	2.05	2.11	2.05
1995	18.09	17.84	14.51	0.18	0.19	0.15	16.23	16.15	12.39	1.86	1.69	2.12
UN	17.47	16.77	13.96	0.19	0.19	0.16	16.12	15.79	12.73	1.35	0.98	1.23
BX	18.94	18.28	14.49	0.21	0.21	0.16	16.43	15.43	11.86	2.51	2.85	2.63
Early sown	19.01	18.09	14.44	0.20	0.20	0.15	17.05	16.08	12.46	1.96	2.01	1.98
Late sown	17.09	16.71	13.91	0.19	0.20	0.16	15.31	15.09	12.18	1.78	1.62	1.73
High N Res.	18.09	17.88	15.31	0.20	0.20	0.17	16.10	15.79	13.73	1.99	2.10	1.59
Low N Res.	18.18	17.04	13.09	0.20	0.19	0.15	16.41	15.47	10.94	1.76	1.57	2.15

The objective of this section is to examine whether or not the differences in biomass production could be explained in terms of the amount of intercepted radiation. The usual form of this analysis is to plot accumulated increments in dry matter against accumulated increments in radiation intercepted. Because measurements of radiation are difficult to make when crops are very small, it is usual to begin measurements in late March or early April. This was the case within the experimental work reported here. This approach removes the small increments of growth prior to March from the analysis and therefore the relationship will become more linear. To examine this, and to determine whether or not the amount of intercepted radiation can account for the change in biomass production, the accumulated increments of biomass from early spring have been plotted firstly against calendar date and secondly against accumulated intercepted radiation. If most of the variation in biomass production is accounted for by radiation interception, the correlation coefficients should be larger than biomass regressed against calendar date.

Figure 40 shows how dry matter production was related to calendar date and radiation interception from 29 March 1993 for all crops grown at the University of Nottingham. The details of the regression lines are presented in Table 34. Although regression against calendar date is an incorrect use of regression because points are not independent, it does give a reasonable but underestimate of the variability in the data. Almost 90% of the variation in crop dry weight was explained by calendar date but this was improved to 94% when dry matter was regressed against intercepted radiation. This improvement was because the nil N crops intercepted less radiation than the fertilised crops. The efficiency of biomass production in relation to radiation intercepted is given by the slope of the regression (e), and is measured in g/MJ. The most efficient crops had values for e of about 1.4 whereas the mean value derived from the fitted regression was 1.12 g DM /MJ.

Regression of crop dry weight against calendar date at ADAS Boxworth in 1993, accounted for 96% of the variation and regression of dry matter against intercepted radiation did not account for any more of the variation. There was no clear separation of any treatments with consistently low or high values of e. The most and least

efficient crops had values of e of 1.18 and 1.42 respectively which were very similar to those measured at the University of Nottingham.
At the University of Nottingham in 1994, dry matter accumulation was poorly related to calendar date because of the large difference in sowing dates; only 81% of the variation was accounted for. Regression against intercepted radiation accounted for 98% of the variation in crop dry matter thus demonstrating the underlying principle of radiation interception controlling crop growth. The most efficient crops had values of e of only 1.26, but the mean e was 1.15, very similar to the mean values in 1993.

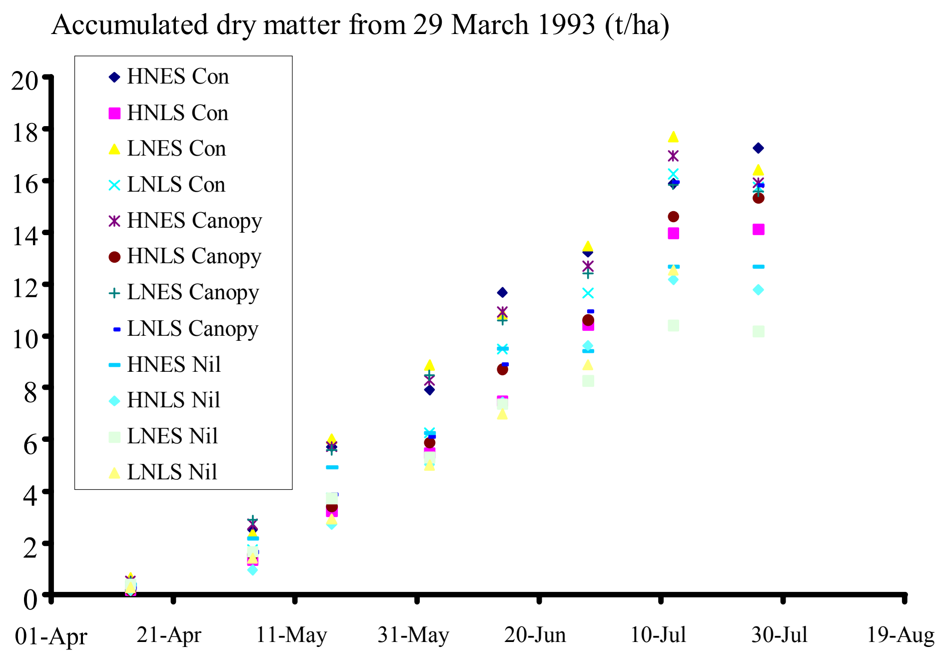
At ADAS Boxworth in 1994, 90% of the variation in dry matter was accounted for by intercepted radiation. Conventional and Canopy Management fertiliser treatments intercepted most radiation whilst the nil N crop sown early into soil with low N residues, produced consistently less dry matter per MJ of intercepted radiation. The most efficient crops had values of e of 1.42, similar to 1993 and the mean efficiency was 1.21.

In 1995, the unfertilised crops growing on soil with low N residues produced consistently less biomass during the season. This was partly because they intercepted less radiation during the season but also because this radiation was converted in dry matter less efficiently. Variation in intercepted radiation accounted for 90% of the variation in dry matter. Departure from linearity was marked during the latter part of the season and appeared to greatest for crops growing where soil N residues were small. Values of e were larger in this year; most efficient crops had values of 1.68 whereas the mean value was 1.40. A similar trend was found at ADAS Boxworth; the unfertilised crop grown on low N residues produced consistently less dry matter per MJ of radiation intercepted. The largest and mean values of e were similar to those measured at the University of Nottingham and were both larger than those measured in 1993 and 1994.

In summary, this analysis so far has shown that dry matter after early spring is strongly related to the accumulation of intercepted radiation which accounted for more of the variation than calendar date. Calendar date was also strongly related to dry matter accumulation and this would be expected because as the season progresses, accumulated radiation can only increase. The largest values of e were similar to those reported in the literature and smallest values were associated with unfertilised crops growing on soils with low N residues. Furthermore, crops tended to be less efficient during the later part of the season. This was most probably the result of senescing leaves intercepting radiation but not contributing to crop photosynthesis.

A more thorough test of the link between radiation interception and dry matter production is to examine for all crops grown at the University of Nottingham and ADAS Boxworth, the link between the amount of radiation intercepted and dry matter produced between firstly, GS31 and GS61 when there is little senescence and secondly from GS61 until mid July during which senescence progresses. These relationships are shown in Figure 46. It is surprising that other influences on crop growth caused so much variation: only 30% of the overall variation in dry matter could be attributed to change in radiation interception during GS31 and GS61. After GS61, the relationship was even weaker, indicating that some crops had very low values of e. In order to examine for underlying causes contributing to this wide variation in e, analyses of variance were conducted on e between GS31 and GS61 and then between GS61 and mid July. A full analysis including season, sowing date, soil N residue and fertiliser treatment could only be conducted for crops grown at the University of Nottingham because of the absence of the late sowings at ADAS Boxworth in 1995 which unbalanced the statistical design.

During pre-anthesis growth (Table 35), crops in 1995 produced significantly more dry matter per MJ of intercepted radiation than in 1993 and 1994. Soil residual N had no effect but early sowings were significantly more efficient. Importantly there was no significant difference in e between the Conventional and Canopy Management treatments whereas unfertilised crops were significantly less efficient. After anthesis, crops in 1994 were significantly more efficient than in 1993, or 1995; the higher e measured before anthesis in 1995 was not maintained through grain filling. The was no difference in e between levels of residual N nor between sowing dates which is surprising because late sown crops would be expected to have less extensive rooting and therefore be more susceptible to drought.



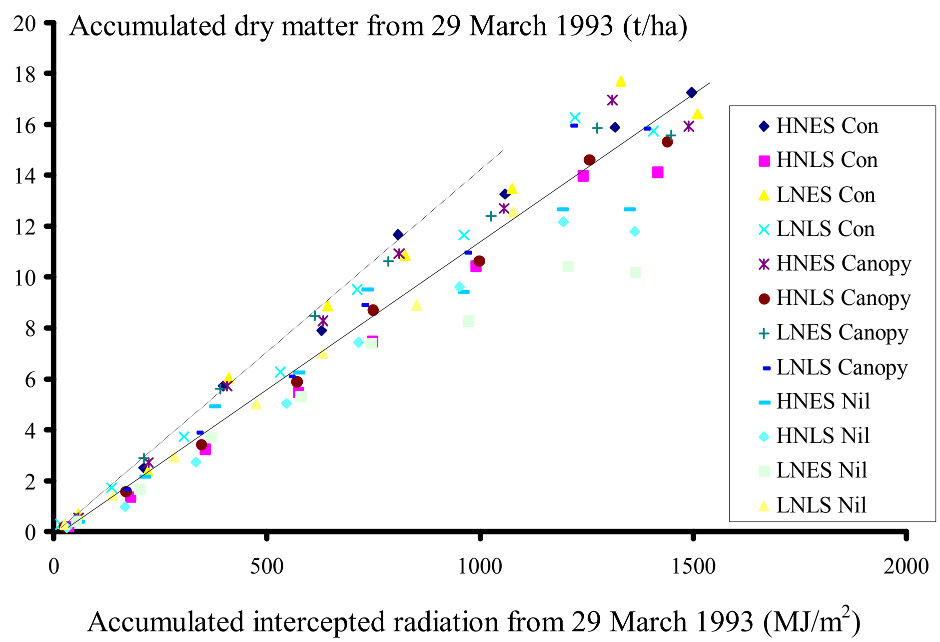
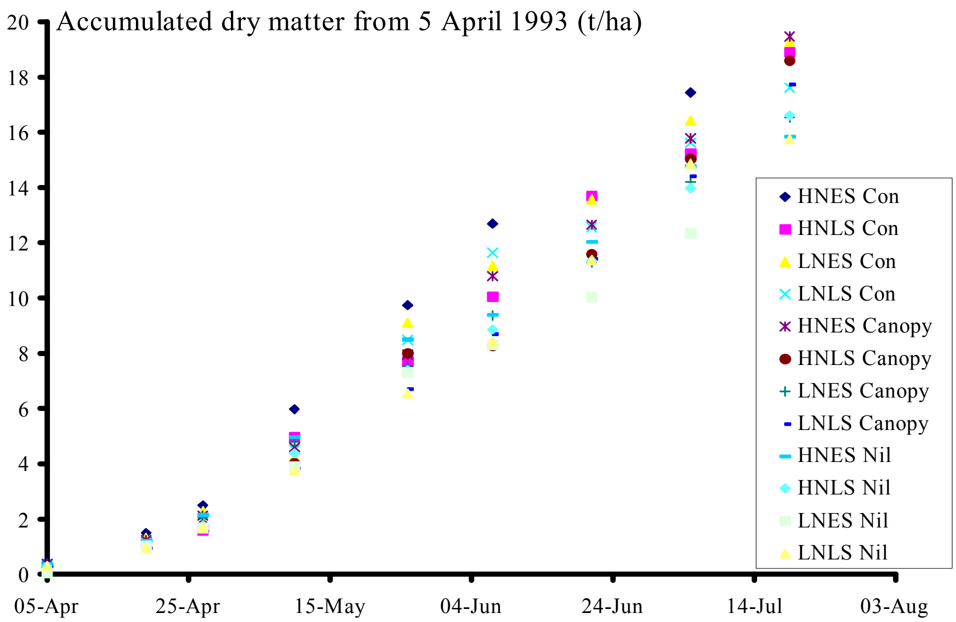


Figure 40 Accumulation of dry matter from 29 March plotted against calendar date and accumulated intercepted radiation for all crops grown at the University of Nottingham in 1993 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regression see Table 34.



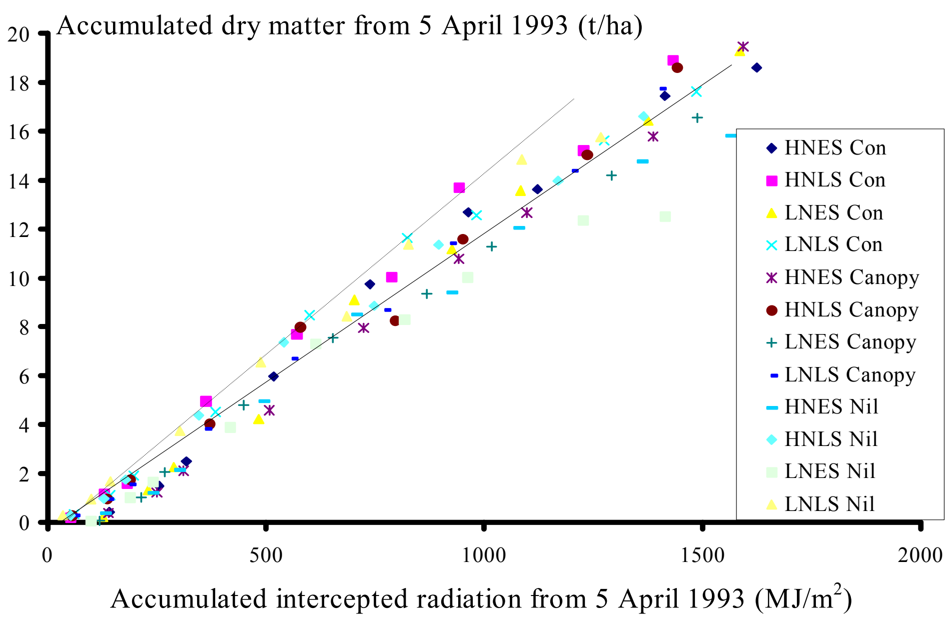


Figure 41 Accumulation of dry matter from 5 April plotted against calendar date and accumulated intercepted radiation for all crops grown at ADAS Boxworth in 1993 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regression see Table 34.

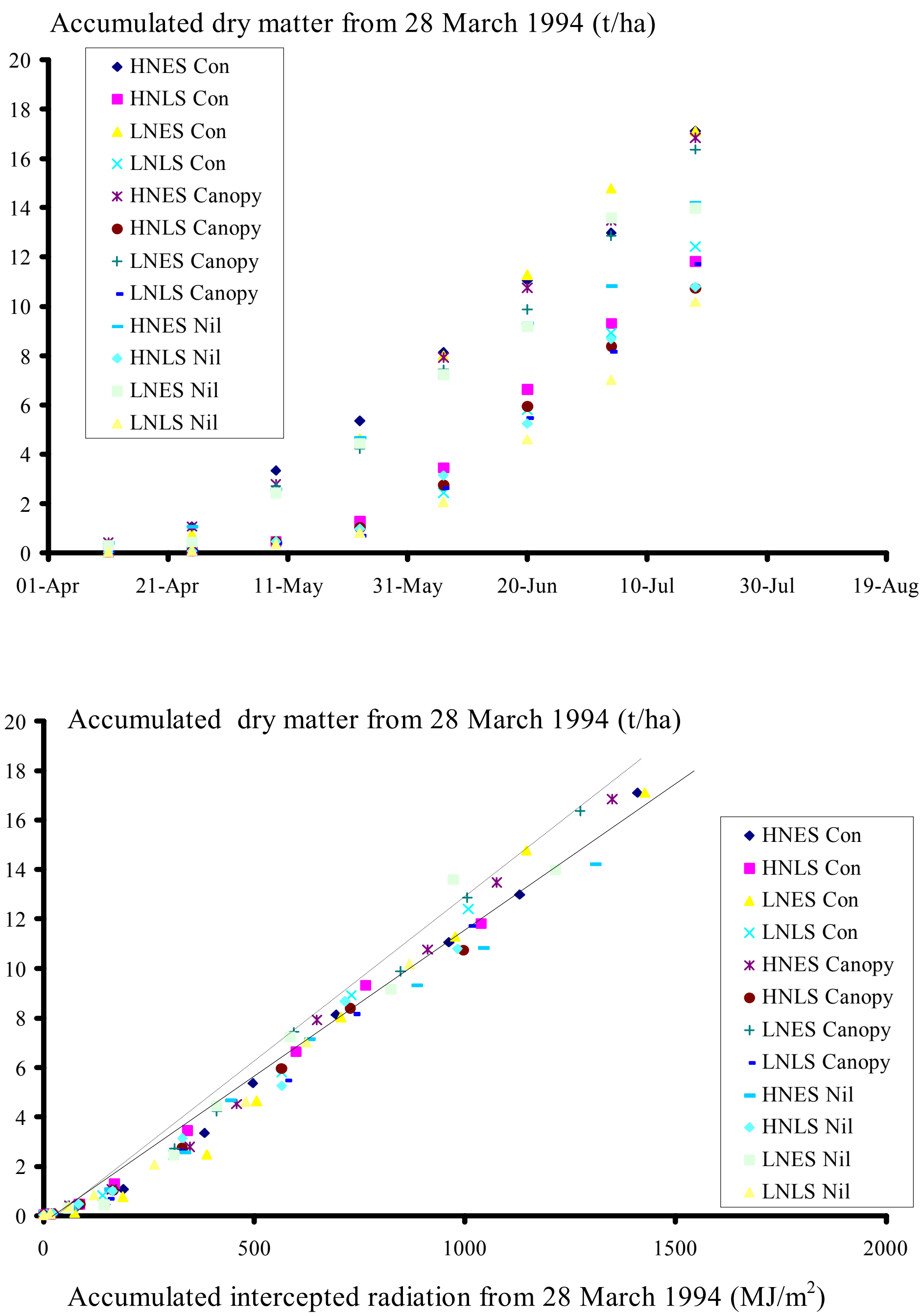
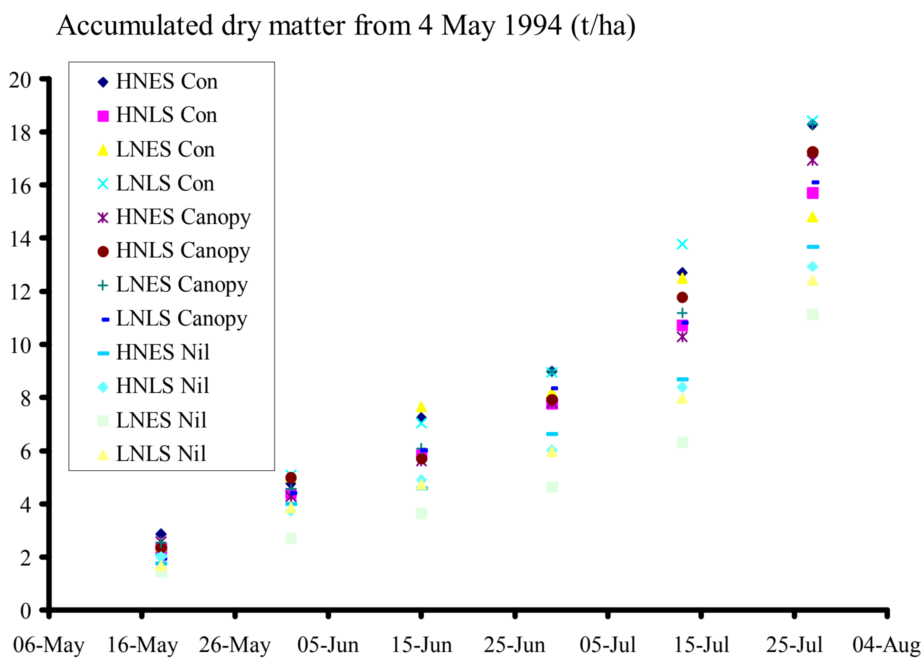


Figure 42 Accumulation of dry matter from 28 March plotted against calendar date and accumulated intercepted radiation for all crops grown at the University of Nottingham in 1994 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regressions see Table 34.



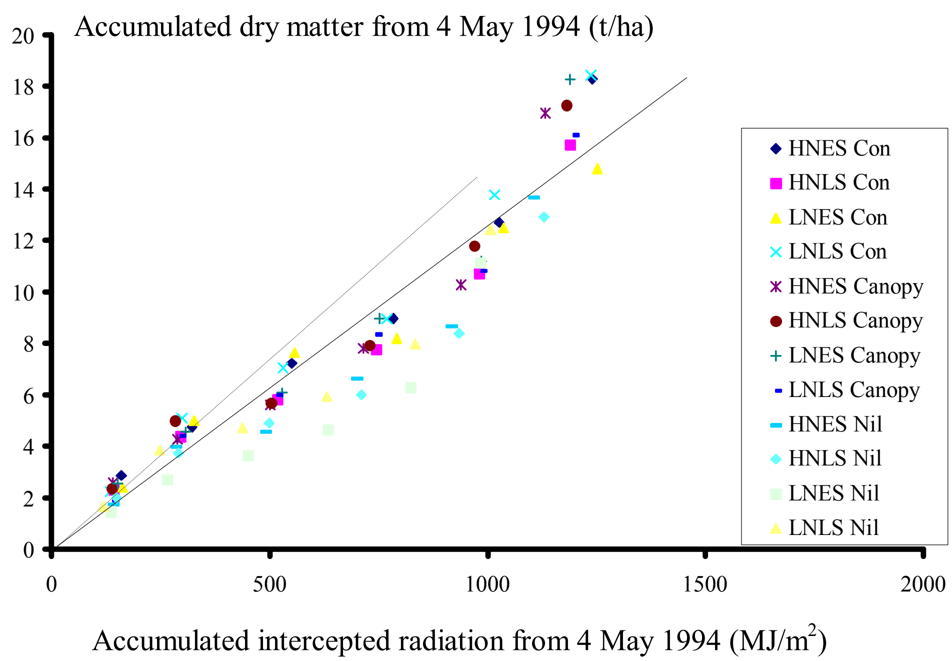
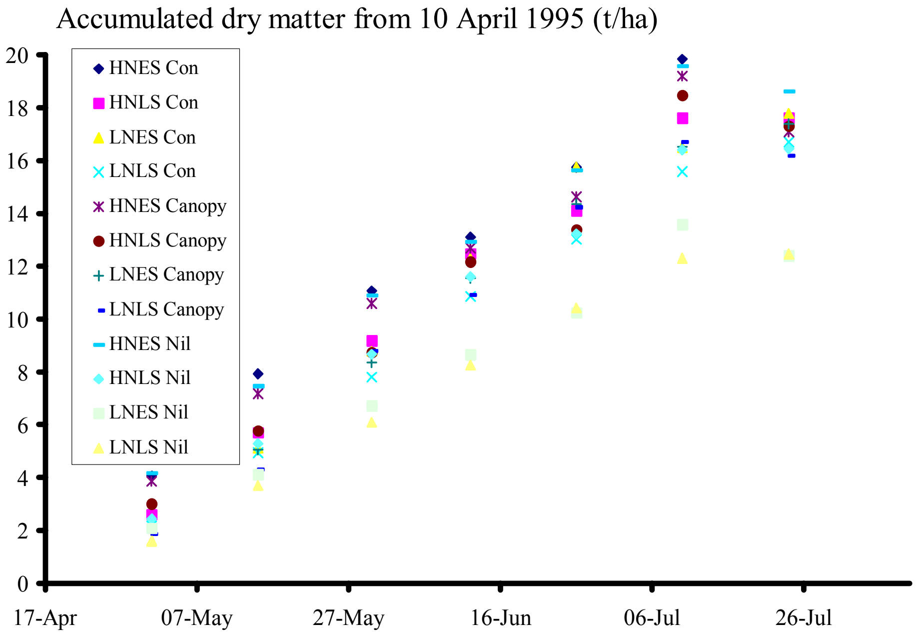


Figure 43 Accumulation of dry matter from 4 May plotted against calendar date and accumulated intercepted radiation for all crops grown at ADAS Boxworth in 1994 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regressions see Table 34.



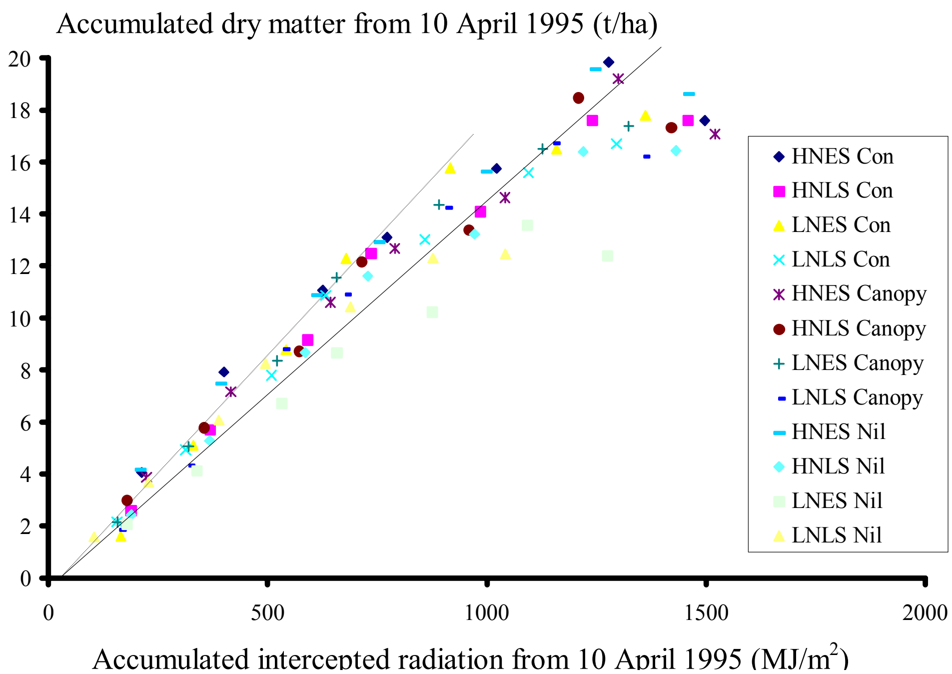
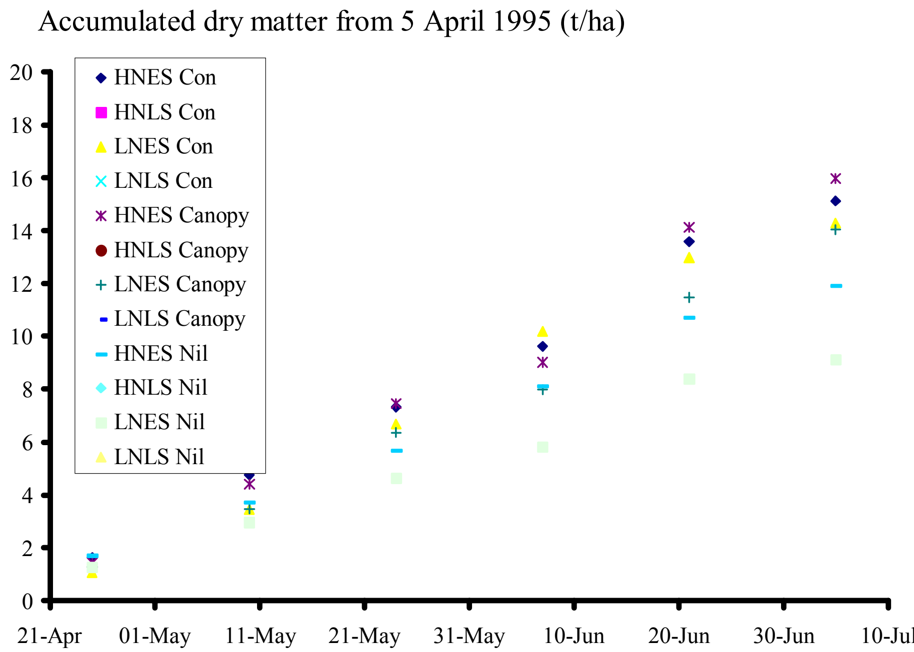


Figure 44 Accumulation of dry matter from 10 April plotted against calendar date and accumulated intercepted radiation for all crops grown at the University of Nottingham in 1995 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regressions see Table 34.



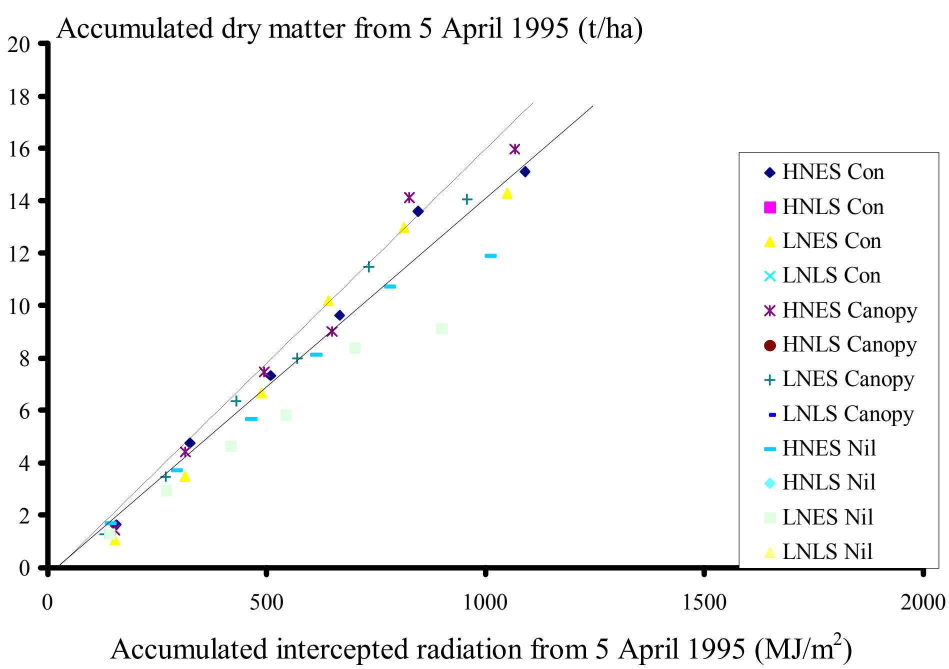
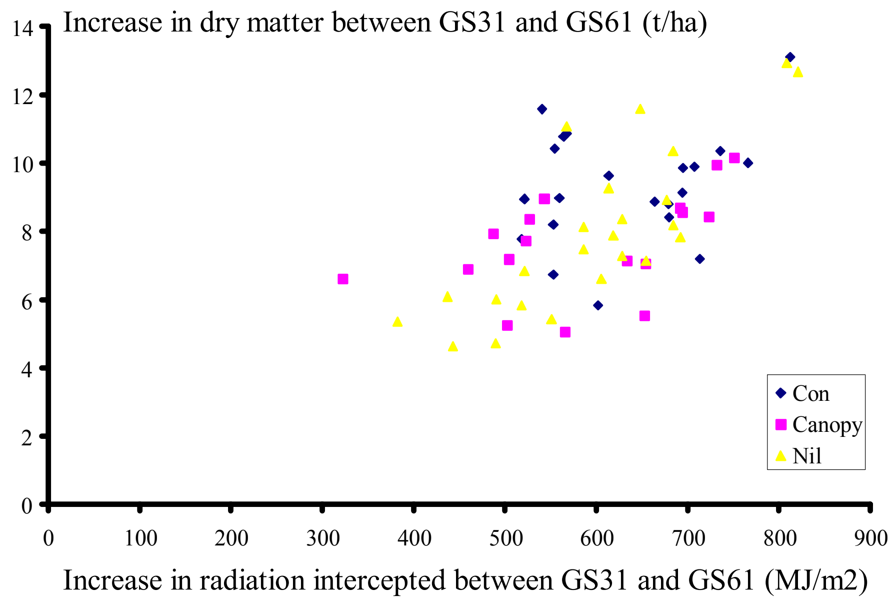


Figure 45 Accumulation of dry matter from 5 April plotted against calendar date and accumulated intercepted radiation for all crops grown at ADAS Boxworth in 1995 receiving conventional (Con), Canopy Management (Canopy) and nil fertiliser N. For details of regressions see Table 34.

Table 34 Correlation coefficients and slopes of regression lines for the relationship between accumulation of dry matter and calendar date and between accumulation of dry matter and accumulation intercepted radiation at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995.

Site	Dry matter and calendar date ***r^2***	Dry matter and intercepted radiation ***r^2***	Dry matter and intercepted radiation (all crops: solid line) ***g/MJ***	Dry matter and intercepted radiation (most efficient crops: broken line) ***g/MJ***
UN 1993	89.8	94.0	1.12	1.40
UN 1994	80.7	97.6	1.15	1.26
UN 1995	87.6	90.0	1.40	1.68
BX 1993	96.1	96.7	1.18	1.42
BX 1994	84.0	90.0	1.21	1.40
BX 1995	89.1	93.5	1.39	1.58



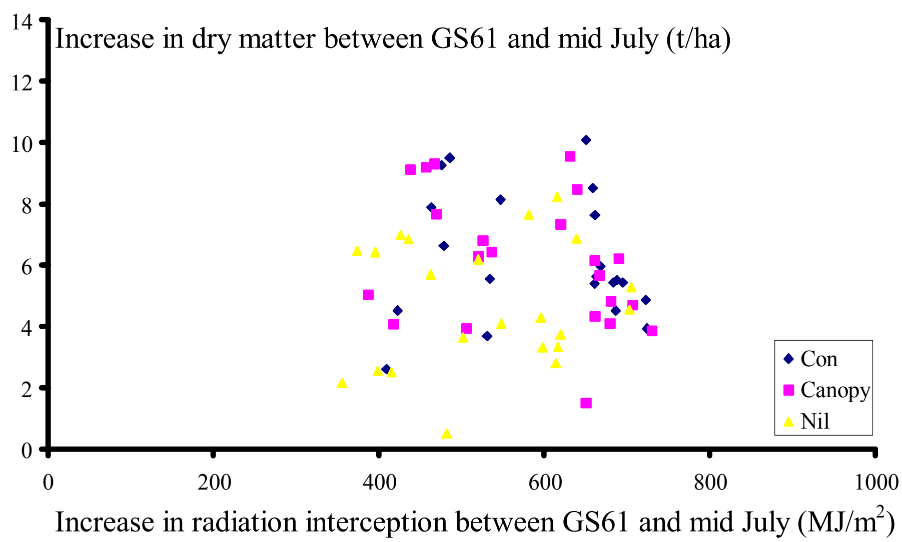


Figure 46 Relationship between radiation interception and dry matter accumulation production between GS31 and GS61 and between GS61 and mid July. Data represent all test crops grown at University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995.

Table 35 Analysis of major variation in efficiency of conversion of intercepted radiation into dry matter before and after anthesis at the University of Nottingham in 1993, 1994 and 1995.

Pre anthesis						
Year	*1993*	*1994*	*1995*	SED	df	Significance
	1.24	1.21	1.78	0.074	4	**
Residual N	*High*	*Low*		SED	df	Significance
	1.40	1.42		0.041	18	NS
Sowing date	*Early*	*Late*		SED	df	Significance
	1.47	1.35		0.041	18	**
N management	*Conventional*	*Canopy*	*Nil*	SED	df	Significance
	1.47	1.44	1.32	0.037	45	***
Post anthesis						
Year	*1993*	*1994*	*1995*	SED	df	Significance
	0.69	1.04	0.69	0.052	4	**
Residual N	*High*	*Low*		SED	df	Significance
	0.79	0.82		0.053	18	NS
Sowing date	*Early*	*Late*		SED	df	Significance
	0.80	0.82		0.053	18	NS
N management	*Conventional*	*Canopy*	*Nil*	SED	df	Significance
	0.85	0.86	0.72	0.059	44	*

The results from this section on biomass production are less clear cut than those from previous sections. There was more variation than expected in the efficiency with which crops converted radiation energy into biomass. Significant amounts of this variation could be attributed to seasonal effects (the lower temperatures and higher radiation receipts in 1995 would have probably increased e prior to anthesis), to change in sowing date and to unfertilised crops. It is important that despite these influences on e, the Canopy Management approach always produced the same value as the conventionally fertilised crops. The theory in the framework linking application of N to yield formation suggested that e would be very conservative across a wide range of conditions; we have shown this not to be the case and further work is required to clearly identify how these changes come about. However, for a given cropping situation, e was not a source of any difference in performance between Canopy Management N and conventional N.

Biomass partitioning and grain yield

In the previous section it was shown that whilst there were significant influences on the efficiency with which energy in sunlight was converted into dry matter, the Canopy Management approach did not reduce ε when compared with conventionally fertilised crops. Therefore it appears that aiming to limit canopy size to more modest levels in May and early June is unlikely to reduce biomass production unless light interception is compromised. The next step is to explore the partitioning of the biomass produced during the season.
Conventional analysis of biomass partitioning usually examines the grain dry matter as a proportion of the total crop dry matter at harvest. This was considered to be inappropriate for this study because it assumes that biomass produced before and after anthesis contributes equally to grain growth. Clearly this was not the case when crops are stressed proportionately more of the stem reserves may be mobilised to maintain grain filling. Thus in the Introduction to this Report we suggested that all the biomass produced after anthesis would be partitioned to grain plus a contribution from stem reserves. Thus in Figure 2, the form of the relationship quantifying biomass partitioning was linear with the intercept on the Y axis indicated the contribution from stem reserves. This form of analysis is more complex than conventional and therefore to determine whether or not a more complex approach is justified, an examination will first be made of the value of the more conventional analysis.

The effect of Conventional, Canopy Management and nil applications of fertiliser N on the relationships between total crop dry matter at harvest and grain yield for all the crops at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995 are presented in Figure 47. Details of the linear regressions are presented in Table 36. From these data it is clear that harvest index was not conservative: total crop dry matter at harvest accounted for 68%, 56% and 93% of the variation in yield of Conventional, Canopy Management and unfertilised crops respectively. The significant intercepts have no physiological meaning as it is impossible to produce grain yield without producing dry matter.

One of the most common causes of variation in harvest index is lodging at harvest and the associated increase in combine losses. In the experiments conducted here, this could not have been the cause; harvest index was calculated from hand harvested samples and no lodging occurred. A possible further explanation may lie in the differential use of stem reserves to maintain grain filling. An example is shown in Figure 48 for crops sown early into soils with high N residues which received Canopy Management applications of N at the University of Nottingham and ADAS Boxworth in 1993. At the University of Nottingham, the non-ear portion of crop decreased by about 3 t/ha during July which maintained ear growth after total crop dry matter had reached maximum. In contrast, at ADAS Boxworth, there was no change in the non-ear portion of crop before ear dry matter had reached maximum. Therefore, stem reserves contributed little to ear growth. If therefore, photosynthesis after anthesis was sufficient to maintain grain filling, it would be expected that there would be little draw on stem reserves and thus at harvest, more dry matter would remain in the stem and consequently harvest index would be smaller than where the draw on stem reserves had been large.

In order to examine the implications of possible differential use of stem reserves, an analysis was undertaken of the movement of dry matter from non-ear crop to the ear. An important part of this analysis was to explore at which point in the development or growth of the crop, the stem reserves began to move. Because in these experiments, only ear dry matter was measured during the season, the following analysis will consider the partitioning of dry matter to whole ears instead of just grain. This is not expected to be at all misleading as the weight of chaff is the same at flowering and at harvest.

The relationship between the increase in total crop dry matter and increase in ear dry matter from mid June until final harvest is presented in Figure 49. There was considerable scatter in the data and just over 60% of the variation in ear growth was accounted for by linear regression. It was considered that a major contribution to the scatter in this relationship might have been differential contribution from reserves. A more accurate analysis of the contribution from stem reserves to ear dry matter can be achieved by examining partitioning to ear growth during two separate phases of ear growth. Firstly, during the period when the increase in ear dry matter was less than the increase in total dry matter hence there was no contribution from stem reserves.

Secondly, during the period when the increase in ear dry matter was greater than the increase in total dry matter and stem reserves must have been contributing to ear growth.

The relationships between increase in ear dry matter and total dry matter when ear growth was firstly less than total growth and secondly, when ear growth was greater than total growth are presented for all the crops in the field tests of Canopy Management in Figure 50. Before stem reserves began to contribute to ear growth, 70% of the increase in total dry matter was partitioned to ears. Linear relationship accounted for 91% of the variation showing that this was extremely conservative. It is interesting that some crops accumulated almost 10 t/ha of dry matter before stem reserves began to move whilst some accumulated only 2 t/ha. This magnitude of difference would suggest that the time at which reserves must have been remobilised must have differed between crops. Furthermore, it is important that the strategy for fertiliser N had no effect on this relationship.

After stem reserves began to contribute to ear growth, the relationship between increase in total dry matter and increase in ear dry matter was still highly significant. Linear regression accounted for 83% of the variation. The highly significant intercept on the Y axis is an estimate of the average contribution from stem reserves i.e. the increase in ear dry matter when there was no further increase in total dry matter, but ear growth continued. This form of analysis is potentially important because it allows an analysis of the contribution from stem reserves without direct measurement of soluble carbohydrate. Variation of data away from the regression line $Y=0.9X + 3.13$ can be considered to be largely the result of differential remobilisation of stem reserves although there could be some contribution from differential respiration. There was no clear overall effect of season, site or sowing date on the relationship between total growth and ear growth (after ear growth was greater than total growth). In order to take a more quantitative approach, it is possible to calculate the theoretical contribution from stem reserves in Figure 50 by determining the additional increase in ear dry matter above line $Y = 0.9 X$. Analysis of these theoretical estimates of contribution from stem reserves are being continued to identify if there were features of crop growth which could account for the change in contribution.

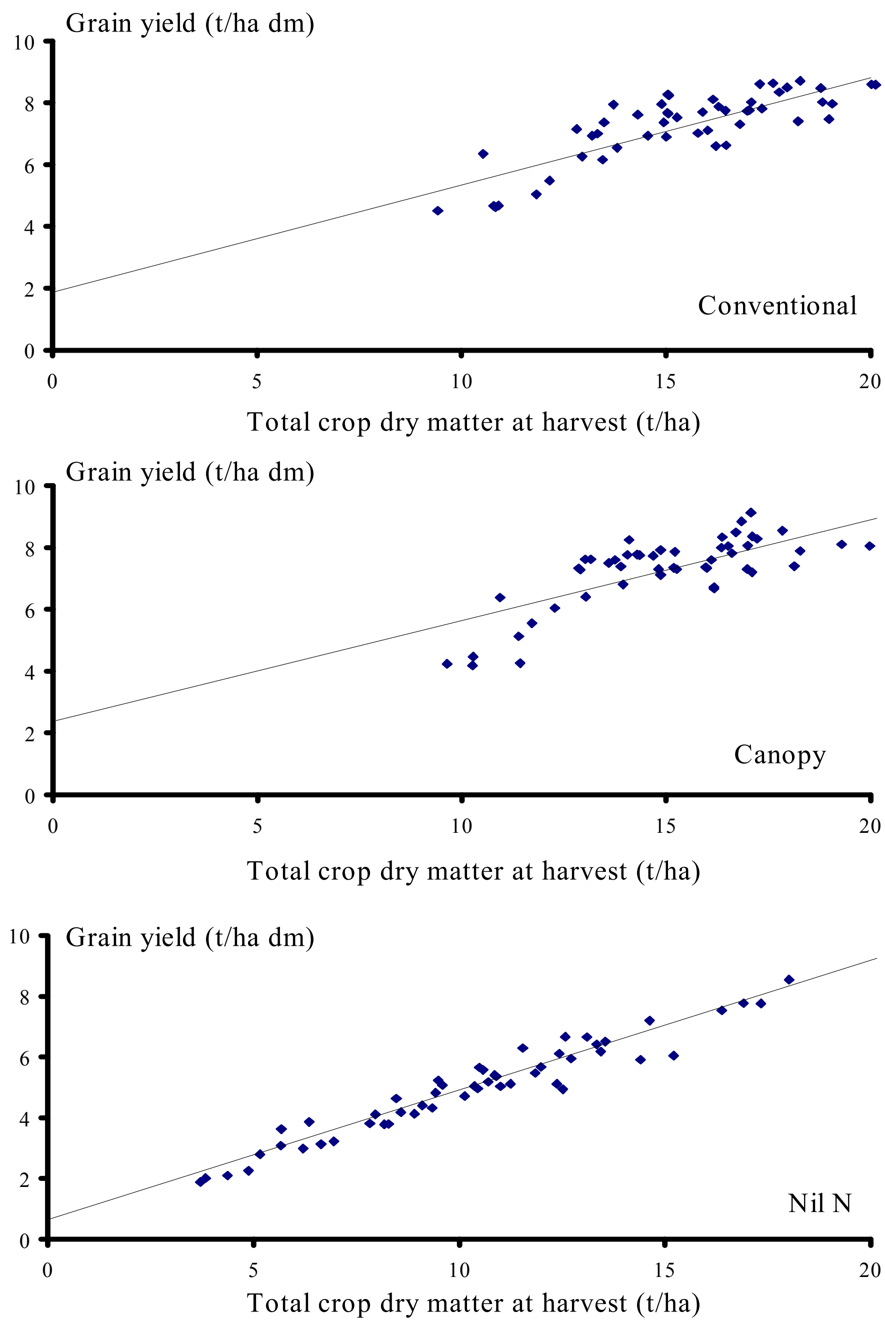
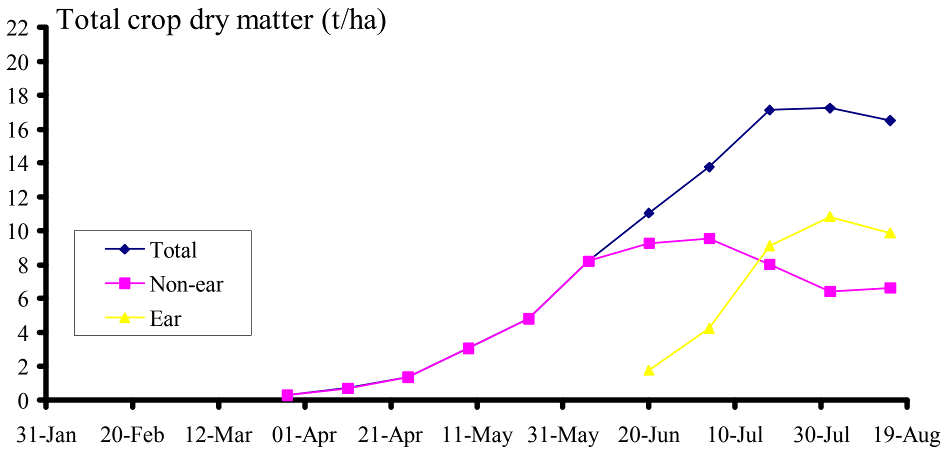


Figure 47 Partitioning of total crop dry matter at harvest to grain for crops receiving Conventional, Canopy Management or Nil fertiliser N applications at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995. Details of the regression lines are given in Table 36.

University of Nottingham 1993



ADAS Boxworth 1993

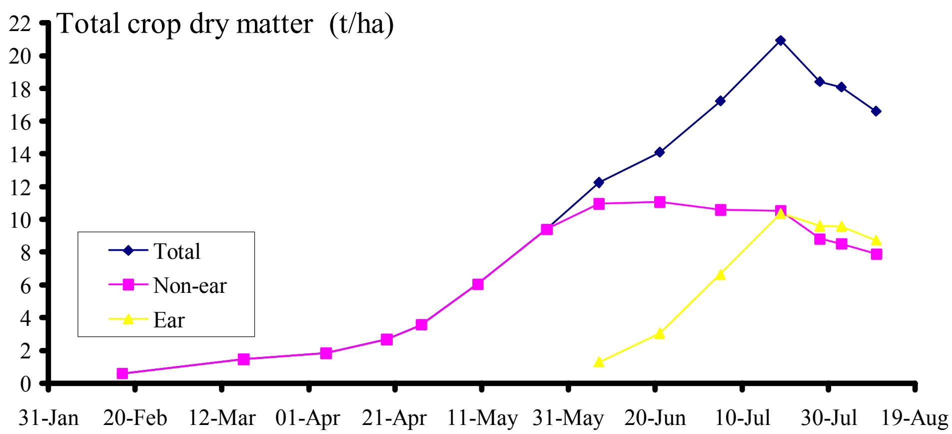


Figure 48 Difference in contribution to ear growth from stem reserves. Examples are taken from the University of Nottingham in 1994 and ADAS Boxworth where Canopy Management was applied to the HNES crop and the contributions from reserves were large and small respectively.

Table 36 Details of the regressions between total crop dry matter at harvest and grain yield presented in Figure 47.

Fertiliser treatment	Correlation coefficient (%)	Slope	Intercept	Significance of intercept
Conventional	67.8	0.35	1.93	P<1.001
Canopy Management	55.6	0.35	2.12	P<0.01
Nil N	93.2	0.43	0.58	P<0.01

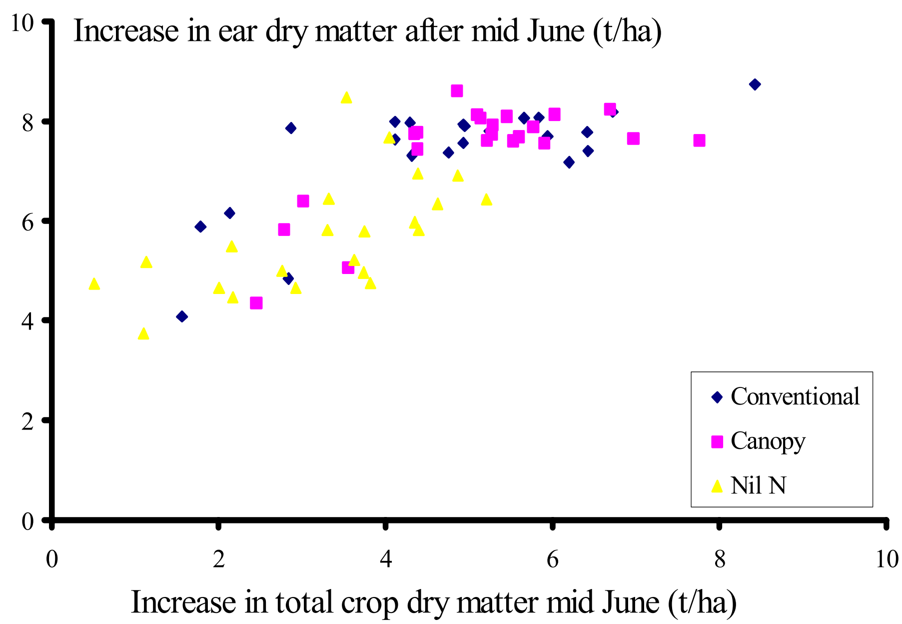
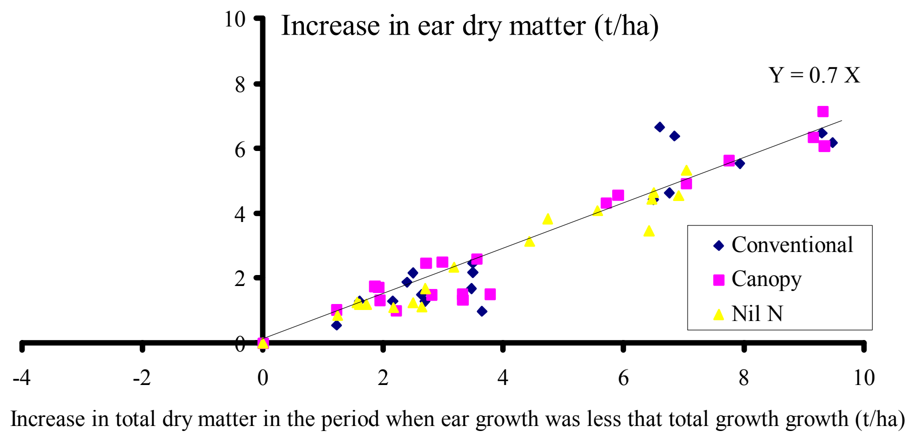


Figure 49 Relationship between increase in total crop dry matter between the first record of ear weight in mid June and final harvest for all crops grown at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995.



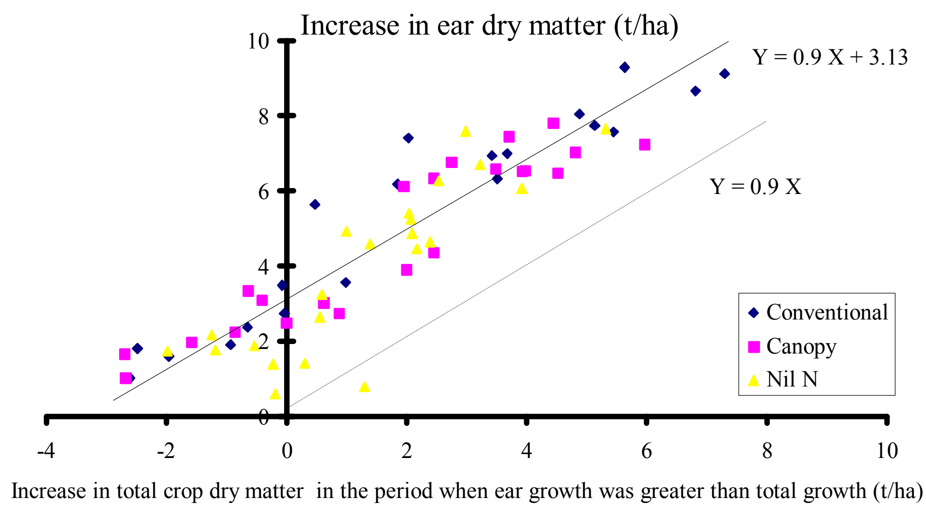


Figure 50 Analysis of the relationship between total growth and ear growth in two phases after the first measurement of ear weight (mid June). Firstly, when ear growth was less than total crop growth and secondly, when ear growth was greater than total growth and stem reserves were contributing to grain filling.

At final harvest, the proportion of the biomass in the form of grain was consistently increased by Canopy Management; on average by more than 2 percentage points and this was highly statitiatically significant (P<0.001) (Table 37). It appears that the small reductions in maximum biomass following Canopy management improved the partitioning of biomass to grain, this is a significant finding because it offers an approach to reduce straw production, commonly an unwanted by product. This will only be of benefit provided grain yields are not compromised by Canopy Management.

The effect of Conventional, Canopy Management and nil N applications on grain yields are presented in Table 38. In 17 out of 24 comparisons Canopy Management produced either the same or greater yields of grain when compared with the Conventional applications. Individually, these responses were not statistically significant but when analysed overall, the effect of Canopy Management (an increase of just over 0.1 t/ha) was significant at ($P<0.07$). These responses to Canopy Management were similar in both early and late sowings and N residue had no significant effects.

Unfertilised crops only, had significantly larger yields (+ 1.2 t/ha) when grown on soils with high N residues thus demonstrating the importance of allowing for the contribution from soil mineral N.

This section on biomass partitioning has shown that the Canopy Management approach effected subtle adjustments to the partitioning of the slightly smaller amount of total biomass produced during the season to result in larger harvest indices and slightly improved yield of grain of grain at harvest.

Table 37 Effect of conventional, Canopy Management and Nil fertiliser N applications on the dry matter harvest index (%) at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995.

			Early sown			Late sown		
Year	Site	N residue	*Conventional*	*Canopy*	*Nil N*	*Conventional*	*Canopy*	*Nil N*
1993	UN	High N	50.8	52.0	49.8	52.6	53.3	52.7
		Low N	49.4	53.7	53.3	49.3	53.6	53.9
1993	AB	High N	40.7	43.3	39.7	40.3	41.0	41.0
		Low N	39.4	44.0	41.4	40.7	42.2	39.5
1994	UN	High N	49.8	50.4	49.2	42.6	44.3	45.5
		Low N	42.7	51.4	49.1	45.1	46.0	48.7
1994	AB	High N	45.0	47.8	46.8	44.4	47.4	47.3
		Low N	45.6	47.0	46.5	43.5	46.4	45.7
1995	UN	High N	41.8	44.7	47.4	40.6	40.8	46.0
		Low N	46.9	47.5	48.4	47.1	46.7	49.0
1995	AB	High N	48.3	48.0	45.9	42.7	45.1	48.7
		Low N	45.8	50.0	46.2	47.9	46.9	48.8
	Mean		***45.5***	***48.3***	***47.0***	***44.7***	***46.1***	***47.2***

Table 38 Effect of conventional, Canopy Management and Nil fertiliser N applications on yields of grain (85% dm) at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995.

			Early sown			Late sown		
Year	Site	N residue	*Conventional*	*Canopy*	*Nil N*	*Conventional*	*Canopy*	*Nil N*
1993	UN	High N	8.86	9.09	6.33	7.92	8.98	6.65
		Low N	8.45	8.84	5.19	8.84	9.16	6.45
1993	AB	High N	8.72	8.48	7.11	7.82	7.88	6.95
		Low N	8.80	8.59	6.02	7.76	7.91	5.81
1994	UN	High N	10.06	9.77	8.37	5.53	5.68	5.83
		Low N	10.13	9.80	7.38	6.28	6.38	6.15
1994	AB	High N	9.19	9.41	7.00	8.36	8.58	6.67
		Low N	9.13	9.48	5.55	8.60	8.67	5.92
1995	UN	High N	9.38	10.05	10.04	8.70	8.70	8.86
		Low N	9.44	9.81	6.09	9.12	9.19	6.31
1995	AB	High N	7.36	7.54	5.84	5.43	4.92	4.92
		Low N	7.25	7.11	4.45	5.31	4.99	4.47
		Mean	***8.90***	***9.00***	***6.61***	***7.47***	***7.59***	***6.25***

Grain quality

The previous section of this report demonstrated that Canopy Management improved the yield of grain in the field tests by more efficiently partitioning the smaller amount of biomass produced during the season. These improvements in yield will only be of benefit in Mercer winter wheat provided grain quality is not compromised. The following sections considers the effects of the Canopy Management approach on breadmaking quality.

Table 39 shows the effects of Conventional, Canopy Management and Nil fertiliser N applications on the partitioning of N to grain at harvest in the field tests of Canopy Management at the University of Nottingham and ADAS Boxworth in 1993, 1994 and 1995. These results bore remarkable similarity to the partitioning of biomass to grain. The Canopy Management approach improved N partitioning to grain in 20 out of 24 comparisons and the overall improvement (+ 3 percentage points) was highly significant ($P<0.001$). The improvements were unaffected by sowing date and soil N residue.

Although N partitioning to grain was proportionately larger in the Canopy Management treatments, there may still be implications for poorer grain quality if total N uptake was reduced or, if the extra grain produced diluted the N (protein) to lower concentrations. Table 40 shows the effect of canopy management on the percent N in the grain, this is an important criteria for breadmaking quality. Canopy Management resulted in an overall increase in the percent N in grain (+0.02%). This small improvement was not statistically significant. However, these results do confirm that the Canopy Management approach is unlikely to have deleterious effects on the N aspects of breadmaking quality.

Table 39 Effect of Conventional, Canopy Management and Nil fertiliser N applications on N harvest index (%) at harvest at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995.

			Early sown			Late sown		
Year	Site	N residue	*Conventional*	*Canopy*	*Nil N*	*Conventional*	*Canopy*	*Nil N*
1993	UN	High N	72.3	76.5	74.6	75.1	76.8	76.2
		Low N	68.1	77.5	77.7	70.6	76.5	79.5
1993	AB	High N	66.2	72.6	69.0	59.5	68.3	70.3
		Low N	63.8	71.2	66.2	60.0	69.8	69.2
1994	UN	High N	78.4	79.1	77.7	73.4	73.4	74.4
		Low N	77.8	79.8	76.2	73.8	73.8	76.5
1994	AB	High N	71.7	73.0	72.7	69.9	75.7	73.1
		Low N	73.0	71.4	72.0	71.5	73.0	71.0
1995	UN	High N	68.7	71.6	72.7	68.5	71.3	72.9
		Low N	76.3	75.2	71.9	78.5	77.0	74.4
1995	AB	High N	79.3	79.5	78.1	74.5	76.5	76.5
		Low N	78.2	80.8	76.3	78.0	77.6	76.2
	Mean		***72.8***	***75.7***	***73.8***	***71.1***	***74.1***	***74.2***

Table 40 Effect of Conventional, Canopy Management and Nil fertiliser applications on % N in grain at harvest at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995.

Early sown	Late sown

Year	Site	N residue	*Conventional*	*Canopy*	*Nil N*	*Conventional*	*Canopy*	*Nil N*
1993	UN	High N	2.25	2.32	1.91	1.89	2.22	1.94
		Low N	2.37	2.21	1.77	2.22	2.07	1.96
1993	AB	High N	2.27	2.19	1.84	2.17	2.37	1.98
		Low N	2.14	2.28	1.84	2.23	2.31	1.87
1994	UN	High N	2.03	2.02	1.61	2.77	2.62	2.39
		Low N	2.11	2.05	1.53	2.54	2.54	1.98
1994	AB	High N	2.04	1.87	1.54	2.00	1.97	1.62
		Low N	2.11	1.91	1.47	2.14	2.22	1.50
1995	UN	High N	2.46	2.51	2.03	2.81	2.90	2.05
		Low N	2.02	2.32	1.49	2.49	2.56	1.49
1995	AB	High N	2.08	2.44	1.95	2.57	2.41	2.21
		Low N	2.37	2.59	1.64	2.38	2.32	1.92
	Mean		***2.19***	***2.23***	***1.72***	***2.35***	***2.38***	***1.91***

Milling and baking tests at CCFRA

Materials and Methods

Milling and baking qualities were assessed on samples from specific sites selected by the Project Steering Group from all plots harvested in 1993, 1994 and 1995. The bases for selection were the effects of treatments on grain yield, and the primary quality characteristics of protein content, Hagberg falling number, specific weight and 1000 grain weight. Resources were available for about 24 analyses from each season, so testing of the wheat samples was restricted to samples deemed appropriate for offer to a miller for inclusion in a bread wheat grist; grain samples with very low protein content, low Hagberg, low specific weight or unacceptable shrivelling were specifically excluded. The main aim was to compare the quality of samples where both the Canopy Management regime and conventional N management gave grain which would have been accepted according to normal basic quality criteria. For this reason there was no consistent sampling plan from one season to the next. Sites, treatments and levels of replication relevant to each of the 3 years are shown in Table 41 .

Milling and baking tests were conducted according to the protocol (Anon, 1992), established in consultation with the milling industry, to examine the quality attributes of new wheat varieties undergoing Recommended List testing in the UK. Tests (marked below) with an FTP reference number are approved by the UK milling and baking industries (Anon, 1991) and are subject to collaborative testing for repeatability and reproducibility. No UK industry standard exists for the Zeleny and Chopin Alveograph tests; these were conducted according to the relevant ICC Standard Methods [(ICC, 1972) (ICC, 1992) and (ICC, 1994)].

Table 41 Sites, treatments and level of replication relevant to tests of milling, breadmaking and export quality.

Year	Sites (level of replication)	Treatments
1993	**University of Nottingham** (3 replicates of 8 treatments)	Residual nitrogen * Sowing date * Spring N (Conventional, Canopy)
1994	**Boxworth** (2 replicates)	Spring N (Conventional, Canopy) (LNES testcrop)
	Rosemaund (2 replicates)	Spring N (Conventional, Canopy) (HNES testcrop)
	University of Nott (2 replicates)	Spring N (Conventional, Canopy) (LNES testcrop)
	Harper Adams (2 replicates of 4 treatments)	Spring N (Conventional, Canopy) (LNES and LNLS testcrops)
1995	**University of Nott** (3 replicates of 6 treatments)	Spring N (Conventional, Canopy, Canopy minus) (LNES and LNLS testcrops)
	Harper Adams (3 replicates of 3 treatments)	Spring N (Conventional, Canopy, Canopy minus)

Results

In 1993, samples were selected from the experiments at the University of Nottingham only but in 1994 and 1995, treatments were selected from more than one site, and results have been analysed considering site and treatment as a single treatment variable in order to test the statistical significance of any effect of Canopy Management.

Milling Quality

Milling quality was assessed as the amount and quality of white flour produced under standard conditions. Milling quality arises from a combination of flour yield, hardness, starch damage and flour colour. Results are presented in Table 42, Table 43 and Table 44. Average flour yields were excellent for all three seasons and unaffected by Canopy Management. The only variable which varied significantly was flour yield in 1994 and observed differences were less than 1%. Given the repeatability of the test, and the high flour yields achieved in 1994, such differences are not considered to be important.

Grain texture appeared to be significantly increased (i.e. % ‘throughs’ on a 75 micron sieve were reduced) by delayed sowing date at the University of Nottingham in 1993. The residual N x sowing date interaction was also statistically significant. However, set against the repeatability value of 3% and the large residual errors observed for this measurement, the overall conclusion is that grain texture was not altered to a commercially significant extent by the Canopy Management regime. Seasonal and site differences in hardness were more pronounced than any apparent difference due to husbandry technique. Mercia samples milled “softer” in 1994 at all four sites; in particular samples from the ADAS Rosemaund and Harper Adams sites would be classified as "borderline soft" on the basis of results from air jet sieving. No obvious explanation can be found for this change in hardness.

Overall, there was no effect on starch damage levels in the flours. At the University of Nottingham in 1993, late sowing appeared to increase starch damage values slightly, but all figures are typical of those observed from a Bühler mill for Mercia.

Only differences between sites significantly affected flour colour values: this is probably a reflection of higher flour protein levels at some sites.

Breadmaking quality

A series of parameters are considered to contribute to final breadmaking quality and mean values for these are tabulated in Table 45, Table 46, Table 47 . Performance in both CBP and Spiral bake systems are of interest, but additional measures such as gel protein and crude protein content help to explain differences in final product quality.

The overall quality of Mercia samples obtained in 1993 was below a typical specification for a CBP bread flour; most treatments produced flour protein contents of less than 10%. Similarly, protein content was rather low in samples from Boxworth and Harper Adams in 1994 and treatments did not increase the quality of grain from these sites to a level which would be accepted at a mill intake for inclusion in a bread grist. In the 1995 experiments, flour protein contents of more than 10% were achieved at both the University of Nottingham and Harper Adams. Flour protein content was significantly reduced by delaying sowing date in 1993. In 1994, the largest influence on flour protein was the site, with Harper Adams producing the smallest average protein content and ADAS Rosemaund the largest. N management within a site had no effect. There was also a significant and pronounced effect on protein content in 1995 due to sowing date at the University of Nottingham. In contrast to 1993, delaying sowing date increased protein content. Canopy Management also produced a significant increase in protein levels compared to conventional N management. These significant treatment effects on protein content can be expected to be reflected in subsequent quality tests, including breadmaking performance.

SDS volumes were generally typical of the variety Mercia and, with the exception of Harper Adams LNLS in 1994, were above the normal value set for acceptance at the mill of around 55 ml. In 1994 site proved to have a significant effect on SDS volume. In particular, SDS values were low at Harper Adams and high at ADAS Rosemaund, reflecting differences in protein content. SDS volume was unaffected by

N management in 1993 or 1994, but significant increases in SDS volume were observed in 1995 when Canopy Management with and without late N were compared with the conventional N treatments. Once again these increases appeared to occur as a result of differences in protein content.

Hagberg falling number values were acceptable at all sites (above 350 seconds) and Canopy Management had no effect on results of this quality test. In 1994, significant differences were observed between sites with ADAS Boxworth and ADAS Rosemaund having high falling numbers and Harper Adams low. This effect represents the normal extent of variation in falling number observed between sites and would have no commercial significance.

Gel protein weight was unaffected by treatments in 1993 and 1994, but both site and treatment, including Canopy Management, had significant effects on gel protein weight in 1995, reflecting differences in crude protein content. However, in general for the variety Mercia, gel protein weights were small in all three seasons.

Protein quality, as measured by gel protein G', was significantly affected by crop management techniques only in 1995. Averaging over all crops, Canopy Management with and without late nitrogen were significantly different (at the 5% P level). This difference reflects changes in crude protein content, suggesting that protein quality improves with increasing flour protein levels. In 1994, G' values were influenced by site. The low protein at Harper Adams resulted in a particularly small G' value, smaller that is normally considered acceptable for UK breadmaking. In 1993, gel protein G' values were generally low at the University of Nottingham; crop husbandry had no effect on this parameter.

N management regimes produced no consistent or significant effect on final quality in either of the CBP or the Spiral mix breadmaking systems. At the University of Nottingham in 1993, sowing date did significantly influence loaf volume, a delay in sowing reduced volumes in both the CBP and Spiral processes. However, this reduction would not be considered commercially significant given the repeatability of the tests and the rather low loaf volume achieved for the early sown crop of Mercia. The observed reduction in loaf volume can be directly related to differences in flour protein content. In samples tested from 1994, no effect of site, treatment or N management had any effect on final breadmaking quality. A site/sowing x spring N interaction was statistically significant at the 5% level in 1995, but examination of the data shows no clear interaction between either spring nitrogen or sowing date.

Export potential

Zeleny sedimentation volumes were not significantly affected by crop husbandry treatments in 1993 (Table 48). In 1994, site influenced zeleny values, reflecting changes in SDS and protein content (Table 49). In 1995, Canopy Management did influence Zeleny values (reflecting effects on SDS sedimentation volume) (Table 50). The Canopy Management treatment without late nitrogen (Canopy minus) produced a significantly lower zeleny volume than the same treatment with late nitrogen (Canopy). However, in all cases, zeleny volumes were greater than 30 ml and therefore likely to meet basic intervention and export standards for wheat.
Sowing date at the University of Nottingham in 1993 significantly affected Alveograph W values. In particular, early sowing resulted in reduced W values (below normal export standards). This result appears to directly conflict with the increases in protein content observed from early sowing, and cannot be explained by differences in previously measured quality parameters. The difference between a W value of 122 and 149, where the test's repeatability is 13.4, is almost within the high margin of error of this test. Highly significant differences in Alveograph W values were observed as a consequence of site/sowing differences in 1994. In particular, the late sowing at Harper Adams resulted in significantly poorer protein strength as measured by Alveograph W, irrespective of N management. Late sown crops at Harper Adams also produced low protein content; this protein weakness confirms the gel protein result. In 1995 Canopy Management appeared to reduce Alveograph W values. Again this contrasts with effects on protein content and gel protein quality. In this season, samples of Mercia generally produced high W values and no treatment resulted in a sample which would be considered unacceptable for export on account of W.

P/L values were unaffected by sites or treatments in 1993 or 1994; however in 1995, site had a major influence on Alveograph P/L values. In particular, P/L was high in samples from Harper Adams. Due to the limited testing it was not possible to determine whether late sowing had any impact on this parameter. All samples produced high P/L values for bread wheat. Thus, in only one instance (the early sowing at the University of Nottingham, harvested in 1995) did these experiments result in Mercia wheat not meeting export specifications.

Discussion

No consistent, significant effects on milling quality resulted from differences in crop husbandry practices; Canopy Management strategies had no apparent effect on milling performance or on the quality parameters associated with this process.

Protein quality combines the influences of genetic constitution, which are considered to be dominant, and environmental factors (due to both climate and husbandry) experienced during crop growth, which are considered to be less important. In this case, our studies were confined to the variety Mercia; thus only environmental effects were observable here.

Many of the quality parameters measured here are interdependent; for instance, there is a positive correlation (r=0.67) between protein content and Alveograph W (Osborne *et al.*, 1992) and recent work has shown a correlation (r=0.77) between flour protein content and CBP loaf volume for Mercia samples differing in protein content from 8.8 to 10.8% (Oliver, 1996). If the Canopy Management approach results in any change in protein content it would also be expected to influence measures of protein quality and ultimately breadmaking quality itself. The maximum difference in protein content associated with the spring N treatments was the effect of using a late fertiliser application (60 kg/ha N) in the Canopy Management regime; this increased protein by almost 1% in 1995. However, results from breadmaking assessments of this material produced no discernible difference in quality in either CBP or Spiral mix breadmaking systems. Other husbandry factors (e.g. sowing date) and site differences, frequently produced more significant effects on breadmaking quality than this. Therefore it can be concluded that the Canopy Management strategy used in this study had no significant effect on breadmaking quality.

The observed increase in gel protein G' values with late nitrogen fertiliser in 1995 confirms previous studies where increases in protein elasticity have been associated with increasing nitrogen levels, particularly when this involved foliar urea applications (Dampney *et al.*, 1995). However, in these studies, all Mercia samples had G' values below 40 Pascals, the reported critical value for G' (Pritchard, 1993) and we would not expect such an increase in protein elasticity to be translated into significant poorer CBP or Spiral mix breadmaking quality.

Previous studies comparing varieties over different seasons have suggested that an inverse relationship exists between protein content and protein quality as measured by gel protein G’ (Salmon *et al*., 1994; Salmon, 1997). Results from the Canopy Management experiments do not fully support this: low protein sites such as Harper Adams in 1994 also produced low protein elasticity. This suggests that site-to-site variation may exert a major influence on protein quality as measured by gel protein elasticity, as is indicated by analyses carried out on grain from Recommended List trials over a number of years (Pritchard , 1993).

At Harper Adams in 1994, delayed sowing reduced the protein content and hence the export potential of the Mercia crop. Both Alveograph W values and Zeleny sedimentation volumes were reduced to levels below acceptability for typical export markets. Protein content was generally low at Harper Adams in 1994 and late sowing exacerbated this.

Table 42 Milling quality of wheat based on 24 grain samples from University of Nottingham, 1993. Values are means for each treatment, averaged across all other treatments. (Con = Conventional, Canopy = Canopy Management with late N)

Treatment	**Level**	**Flour yield %**	**Grain texture %**	**Starch damage FU**	**Grade colour GCF**
Residual N	High	79.41	37.3	28.3	-0.08
	Low	79.38	37.92	28.7	0.24
Sowing date	Early	79.47	38.36	27.0	0.06
	Late	79.32	36.87	29.9	0.10
Spring N	Con	79.21	37.61	28.6	0.16
	Canopy	79.58	37.62	28.3	0.01
Grand Mean		79.40	37.61	28.5	0.08
SED	Residual N or sowing date	0.32	0.21	1.1	0.26
	Spring N	0.20	0.42	0.6	0.11

Table 43 Milling quality of samples selected from Boxworth, Rosemaund, University of Nottingham and Harper Adams, 1994. Values for each site are means across spring N treatments, and values for spring N treatments are means across sites. (Con = Conventional, Canopy = Canopy Management with late N)

	Treatment	**Flour yield %**	**Grain texture %**	**Starch damage FU**	**Grade colour GCF**
Boxworth	LNES	82.10	49.30	37.8	-0.05
Rosemaund	HNES	81.80	53.52	35.5	1.71
University of Nott	LNES	82.25	48.70	38.8	1.00
Harper Adams	LNES	81.28	52.17	37.8	0.96
Harper Adams	LNLS	81.50	55.77	32.5	0.15
Spring N	Con	81.73	52.29	35.4	0.77
	Canopy	81.84	51.50	37.5	0.73
Grand Mean		81.79	51.89	36.5	0.75
SED	Crop	0.19	0.99	1.9	0.33
	Spring N	0.12	0.62	1.2	0.21

Table 44 Milling quality of samples selected from University of Nottingham (Sutton Bonington) and Harper Adams, 1995. Values for each site and sowing are averaged across 3 spring N treatments and values for each spring N treatment are averaged across the 3 sites/sowings. . (Con = Conventional, Canopy = Canopy Management with late N, Canopy minus = Canopy Management without late N).

	Treatment	**Flour yield %**	**Grain texture %**	**Starch damage FU**	**Grade colour GCF**
University of Nott	Early Sown	81.38	37.37	31.3	-0.76
University of Nott	Late Sown	80.99	38.0	31.6	-0.09
Harper Adams	Late Sown	80.94	36.58	34.0	0.42
Spring N	Con	81.18	37.49	32.0	-0.19
	Canopy minus	81.15	37.28	32.1	-0.34
	Canopy	80.97	37.14	32.8	0.09
Grand Mean		**81.10**	**37.3**	**32.3**	**-0.14**
SED	Site/sowing or Spring N	0.21	0.77	1.18	0.12

Table 45 Breadmaking quality of wheat based on 24 grain samples from University of Nottingham, 1993. Values are means for each treatment, averaged across all other treatments. . (Con = Conventional, Canopy = Canopy Management with late N).

Treatment	**Level**	**SDS volume** ml	**Flour Protein** % at 14 MC	**Hagberg falling no.** s	**CBP loaf volume** ml	**CBP crumb score** (0-10)
Residual	High	59.2	9.50	350	1410	6.8
	Low	59.5	9.84	350	1397	6.4
Sowing date	Early	59.2	10.02	357	1426	6.8
	Late	59.6	9.33	343	1381	6.4
Spring N	Con	60.1	9.78	351	1423	6.8
	Canopy	58.6	9.57	350	1384	6.4
Grand Mean		59.4	9.67	350	1431	6.6
SED	Residual N / sowing date	1.2	0.18	7.8	12.7	0.3
	Spring N	0.7	0.14	3.5	11.6	0.2

Table 46 Breadmaking quality of samples selected from Boxworth, Rosemaund, Sutton Bonington and Harper Adams, 1994. Values for each site are means across spring N treatments, and values for spring N treatments are means across sites. . (Con = Conventional, Canopy = Canopy Management with late N).

Treatment	**Level**	**SDS volume** ml	**Flour Protein** % at 14 MC	**Hagberg falling no.** s	**CBP loaf volume** ml	**CBP crumb score** (0-10)
Boxworth	LNES	63.8	9.18	409	1614	7.5
Rosemaund	HNES	68.5	10.00	403	1630	7.4
University of Nott	LNES	66.1	9.73	379	1577	6.6
Harper Adams	LNES	57.8	9.05	353	1580	6.8
Harper Adams	LNLS	53.3	8.38	350	1561	7.4
Spring N	Con	61.4	9.36	380	1601	7.2
	Canopy	62.3	9.17	378	1585	7.1
Grand Mean		61.9	9.27	379	1593	7.1
SED	Crop	2.2	0.31	13.5	23.9	0.5
	Spring N	1.4	0.20	8.6	15.11	0.3

Table 7.

Table 47 Breadmaking quality of samples selected from University of Nottingham (Sutton Bonington) and Harper Adams, 1995. Values for each site and sowing are averaged across 3 spring N treatments and values for each spring N treatment are averaged across the 3 sites/sowings. (Con = Conventional, Canopy = Canopy Management with late N, Canopy minus = Canopy Management without late N).

	Treatment and level	**SDS volume** ml	**Flour Protein** % at 14 MC	**Hagberg falling no. s**	**CBP loaf volume** ml	**CBP crumb score** (0-10)
University of Nott	Early Sowing	64.2	9.51	371	1381	6.0
University of Nott	Late Sowing	67.0	10.66	376	1397	6.1
Harper Adams	Late Sowing	64.7	10.46	341	1405	6.1
Spring N	Con	64.0	10.06	363	1394	6.1
	Canopy minus	62.6	9.79	355	1401	6.1
	Canopy	69.3	10.78	370	1389	6.1
Grand Mean		65.3	10.21	363	1395	6.1
SED	Crop or Spring N	0.71	0.33	10.9	9.5	0.1

Table 48 Export quality of wheat based on 24 grain samples from University of Nottingham, 1993. Values are means for each treatment, averaged across all other treatments. (Con = Conventional, Canopy = Canopy Management with late N).

Variable	**Level**	**Alveograph, W** (Joules x 10^{-4})	**Alveograph** P/L	**Zeleny volume** ml
Residual N	High	130.3	0.97	34.9
	Low	141.4	1.08	37.5
Sowing date	Early	122.3	1.02	34.7
	Late	149.4	1.04	37.7
Spring N	Normal	135.4	0.93	38.1
	N5 plus	136.3	1.13	34.3
Grand Mean		135.9	1.03	36.2
SED	Residual N / sowing date	6.71	0.1	2.6
	Spring N	4.01	0.11	1.9

Table 49 Export quality of samples selected from Boxworth, Rosemaund, Sutton Bonington and Harper Adams, 1994. Values for each site are means across spring N treatments, and values for spring N treatments are means across sites. . (Con = Conventional, Canopy = Canopy Management with late N).

Variable	**Level**	**Alveograph, W** (Joules x 10 $^{-4}$)	**Alveograph** P/L	**Zeleny volume** ml
Boxworth	LNES	190.3	1.34	31.5
Rosemaund	HNES	196.0	1.35	37.0
University of Nott	LNES	206.8	0.85	32.5
Harper Adams	LNES	185.4	0.97	30.3
	LNLS	129.0	0.74	25.8
Spring N	Con	175.4	0.91	31.3
	Canopy	187.6	1.19	31.5
Grand Mean		181.5	1.05	31.4
SED	Crop	11.7	0.21	1.8
	Spring N	7.4	0.13	1.2

Table 50 Export quality of samples selected from University of Nottingham and Harper Adams, 1995. Values for each site and sowing are averaged across 3 spring N treatments and values for each spring N treatment are averaged across the 3 sites/sowings. (Con = Conventional, Canopy = Canopy Management with late N, Canopy minus = Canopy Management without late N).

	Level	**Alveograph, W** (Joules x 10 $^{-4}$)	**Alveograph** P/L	**Zeleny volume** ml
University of Nott	Early Sowing	155.7	0.96	33.0
University of Nott	Late Sowing	151.6	0.94	37.3
Harper Adams	Late Sowing	167.0	1.34	40.2
Spring N	Con	149.4	1.03	35.9
	Canopy minus	178.7	1.11	32.9
	Canopy	146.2	1.10	41.8
Grand Mean		**158.1**	**1.08**	**36.9**
SED	Treatment or Spring N	10.7	0.08	1.5

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Economics of Canopy Management

The evidence presented in this report has demonstrated that the Canopy Management approach to fertilising winter wheat resulted in slightly improved yields of grain of similar quality to Conventional applications. The approach had the further advantage of generally reducing the amount of N applied in most of the comparisons in the field tests. This sections presents an analysis of the benefit derived from adopting the Canopy Management approach. For this, grain was assumed to be worth 10p /kg and fertiliser N worth 30 p/kg. The cost of analysis for soil mineral N in February was taken to be £2 /ha when conducted on a commercial scale.

Canopy Management resulted in yield improvements of 0.14, 0.08 and 0.04 t/ha in 1993, 1994 and 1995 respectively with an average savings in N of 35 and 10 kg/ha in 1993 and 1994 respectively however, slightly more N (16 kg/ha) was used compared with conventional applications in 1995. Comparing the value of the yield improvements and the changes in N use together with the cost for analysis of soil mineral N, Canopy Management resulted in an overall benefit of nearly £10 /ha. The financial return was less in 1995 because of the increase in N use.

These results are very encouraging because it demonstrates that the Canopy Management approach which was derived entirely from a physiological understanding of crop processes, gave an improved financial benefit when compared with the Conventional approach.

Table 51 Analysis of the financial benefit from Canopy Management at the University of Nottingham (UN) and ADAS Boxworth (AB) in 1993, 1994 and 1995. Grain and fertiliser N were assumed to be worth 10p and 30p per kilo respectively and the probable cost of commercial analysis of soil mineral N was taken to be £2/ha.

Year	Site	Background crop	Nil N Yield (t/ha 85%dm)	Conventional N applied (kg/ha)	Conventional Yield (t/ha 85%dm)	Canopy N applied (kg/ha)	Canopy Yield (t/ha 85%dm)	Difference in Grain yield (t/ha)	Difference in N applied (kg/ha N)	Value of Extra grain £/ha	Value of saving in N £/ha	Overall benefit £/ha
1993	UN	HNES	6.36	190	8.99	170	9.11	0.12	-20	12	6	16
		HNLS	6.56	180	8.24	150	8.96	0.72	-30	72	9	79
		LNES	5.46	210	8.68	190	8.95	0.27	-20	27	6	31
		LNLS	6.65	200	8.86	180	9.14	0.28	-20	28	6	32
1993	AB	HNES	7.11	140	8.72	100	8.48	-0.24	-40	-24	12	-14
		HNLS	6.95	130	7.80	90	7.86	0.06	-40	6	12	16
		LNES	6.02	190	8.80	130	8.59	-0.21	-60	-21	18	-5
		LNLS	5.81	180	7.76	130	7.91	0.15	-50	15	15	28
1994	UN	HNES	8.47	170	10.13	130	9.84	-0.29	-40	-29	12	-19
		HNLS	6.02	160	5.94	120	6.03	0.09	-40	9	12	19
		LNES	7.18	190	10.11	160	9.99	-0.12	-30	-12	9	-5
		LNLS	5.94	180	6.46	170	6.54	0.08	-10	8	3	9
1994	AB	HNES	7.00	140	9.19	150	9.41	0.220	10	22	-3	17
		HNLS	6.67	130	8.36	150	8.58	0.221	20	22	-6	14
		LNES	5.55	190	9.13	200	9.48	0.35	10	35	-3	30
		LNLS	5.92	180	8.60	180	8.67	0.07	0	7	0	5
1995	UN	HNES	10.04	160	9.38	140	10.05	0.67	-20	67	6	71
		HNLS	8.86	150	8.70	170	8.70	0.00	20	0	-6	-8
		LNES	6.09	190	9.44	230	9.81	0.37	40	37	-12	23
		LNLS	6.31	180	9.12	230	9.19	0.07	50	7	-15	-10
1995	AB	HNES	5.84	140	7.36	200	7.54	0.18	60	18	-18	-2
		HNLS	4.92	130	5.44	120	4.92	-0.52	-10	-52	3	-51
		LNES	4.45	190	7.25	240	7.11	-0.14	50	-14	-15	-31
		LNLS	4.49	180	5.31	120	4.99	-0.32	-60	-32	18	-16
Mean	***1993***		***6.37***	***178***	***8.48***	***143***	***8.63***	***0.14***	***-35***	**14.38**	**10.50**	**22.88**
Mean	***1994***		***6.59***	***168***	***8.49***	***158***	***8.57***	***0.08***	***-10***	**7.76**	**3.00**	**8.76**
Mean	***1995***		***6.38***	***165***	***7.75***	***181***	***7.79***	***0.04***	***16***	**3.88**	**-4.88**	**-3.00**
		Overall mean	***6.44***	***170***	***8.24***	***160***	***8.33***	***0.09***	***-10***	**8.67**	**2.88**	**9.55**

Discussion

Financial and representational considerations

The results section of this report has detailed the outcome of the tests of Canopy Management at the University of Nottingham and ADAS Boxworth during the three year investigation. These results have provided valuable support for the principles underlying the approach to Canopy Management and effects on grain yield and quality are encouraging.

In addition to the tests at these two main sites, there were tests at satellite sites where the approach was tested across a wider range of conditions. The outcome from these further tests will now be considered in terms of yields, N use and financial performance. The series of further tests can be divided into two categories. Firstly where the outcome was broadly similar to that at the University of Nottingham and ADAS Boxworth. And, secondly, where the outcome was less favourable.

Firstly, at all satellite sites in 1993 and at ADAS Rosemaund and Harper Adams in 1994, and at Harper Adams and SAC Edinburgh in 1995, the financial outcome was generally commensurate with that from the University of Nottingham and ADAS Boxworth. The results from the above sites indicate that the Canopy Management approach resulted in slight savings in N with increases in yield with concomitant increased financial return (Table 52).

However, at Arable Research Centres, Cirencester and ADAS Terrington in 1994 and 1995 and at ADAS Rosemaund and ADAS High Mowthorpe in 1995, the results were less favourable (Table 53). Moderately large financial losses were incurred because of reductions in grain yield, averaging 0.42 t/ha. The explanation for these losses is unclear; the absence of detailed growth analyses during the season restricts the scope of any interpretation. However, the somewhat circumstantial evidence can be assembled and suggestions made for further experimentation.

The sites at ARC Cirencester and at ADAS High Mowthorpe were highly calcareous; similarly poor performance of Canopy Management was noted at recent demonstrations (Cereals ‘95 and Cereals ‘96) on similarly shallow soils in Lincolnshire. Recent analyses of extensive MAFF-funded experiments on shallow soils over chalk have shown that recovery of fertiliser N is significantly poorer here than on the heavier and deeper soils typified by the core experiments of this Project at Sutton Bonington and ADAS Boxworth. In fact, best N recovery has been noted on sandy soils such as those at Harper Adams. It may therefore be necessary to adjust the 'rules' for Canopy Management for such sites as these, to provide for adequate N uptake for canopy formation.

Table 52 Benefit from Canopy Management with late N compared with Conventional N at the sites where the results were generally commensurate with those from the University of Nottingham and ADAS Boxworth.

Year	Site	Background crop	Change in yield (t/ha)	Saving in N (kg/ha)	Value of yield change £/ha	Value of N saved £/ha	Benefit £/ha
1993	TR	HNES	0.20	50	20	-15	3
		HNLS	0.40	60	40	-18	20
		LNES	-0.32	0	-32	0	-34
		LNLS	0.22	20	22	-6	14
1993	RO	HNES	0.76	10	76	-3	71
		LNES	0.24	0	24	0	22
1994	RO	HNES	0.48	-60	48	18	64
		LNES	0.11	-90	11	27	36
1994	HA	LNES	0.10	0	10	0	8
		LNLS	0.16	20	16	-6	8
1995	HA	LNES	0.52	10	52	-3	47
		LNLS	0.31	30	31	-9	20
1995	ED	LNES	0.30	50	30	-15	13
		LNLS	0.03	50	3	-15	-14
	1993 Mean		**0.25**	**23.33**	**25.00**	**-7.00**	**16.00**
	1994 Mean		**0.21**	**-32.50**	**21.25**	**9.75**	**29.00**
	1995 Mean		**0.29**	**35.00**	**29.00**	**-10.50**	**16.50**
	Overall mean		**0.25**	**10.71**	**25.07**	**-3.21**	**19.86**

It is also the case that all these unfavourable comparisons occurred in 1994 and 1995, seasons characterised by below average summer rainfall and therefore (on some soils) conducive to drought. Here it is thought that the poorer performance from Canopy Management could be linked to an inhibition of deep root formation, or to poorer production of stem reserves for subsequent remobilisation to grain. With the delay in application of early doses of N, despite sufficient N being available in these soils to satisfy the requirements for canopy expansion, it is possible that there was inadequate early uptake to stimulate the deep rooting that would be necessary to maintain water uptake through to the end of grain filling. On the deep silty soils at ADAS Terrington and ADAS Rosemaund it is less likely that there would have been a deficiency in available water, even in the very dry season of 1995, as long as rooting was adequate. However it may be that, even on this soil, the dry soil surface may have delayed access to the fertiliser N, inhibiting both canopy formation and deep root formation.

As is discussed below, it is also the case that Canopy Management resulted in production of fewer shoots and a smaller weight of straw per hectare. If this arose more through decreased production of stem material than through increased remobilisation of stem material, it may be that Canopy Management was compromised in the dry (or otherwise stressed) conditions during grain fill through having less reserve material available from the stems.

Considering all the unfavourable comparisons, it certainly appears that there could be a link between fertiliser N and available soil moisture. It may be that early N, in excess of that required to form the required canopy size for radiation interception, is required to stimulate both root and shoot proliferation. We would thus identify the link between N supply and soil moisture as an area for further investigation. We are making some attempt to examine this as part of Project 0023/1/95 ‘The value of crop intelligence to wheat growers’.

It is not straightforward to make an overall comparison of Canopy Management with Conventional N management for all sites, since there were not equivalent numbers of treatments at each site and not equivalent numbers of sites in each year. Given that there appears to be a link between dry conditions and unfavourable performance of Canopy Management it would also seem important that the evident success of Canopy Management shown at the core sites does not become compromised due to the over-representation of dry conditions in these satellite comparisons. It would be ideal if dry conditions could be represented in the same proportion as they occur over the range of sites, and over the run of years during which growers should take these results into account. However, there would be an unacceptable degree of uncertainty attached to making such an adjustment to the results.

We have therefore chosen not to make an overall financial summary, but to leave the Project with a general conclusion that Canopy Management has been shown to have a number of advantageous features and that in circumstances common to wheat production in the UK, these amount to an overall financial benefit. However, there are likely to be a minority of circumstances, particularly on drought-prone soils, in which Canopy Management does not out-perform conventional fertiliser practices.

It must be remembered that these financial analyses do not take into account the potential extra savings with Canopy Management associated with reduced use of fungicides and plant growth regulators resulting from reduced pressure from disease and lodging because the crops were less lush and dense. These issues are more comprehensively addressed in reports on parallel projects which have studied the interactions between Canopy Management and the control of yellow rust, grain aphids and lodging (MAFF Project CSA2149 and HGCA Project 0050/1/92).

Scientific considerations

The objective of this work was to assess and develop the concept of 'Canopy Management' with N. The term 'Canopy Management' was adopted, through this Project, to describe a rationale for wheat husbandry whereby inputs such as nitrogen are optimised according to their effects on the size of the crop's green canopy, and hence on it's photosynthetic capacity. 'Canopy Management' was seen as an alternative to the more conventional approach whereby husbandry inputs, particularly nitrogen, are adjusted in proportion to 'expected yield'.

Table 53 Effects of Canopy Management with late N compared with Conventional N management at sites where reductions in yield were experienced.

Year	Site	Background	Change in	Saving	Value of	Value of	Benefit

		crop	yield (t/ha)	in N (kg/ha)	yield change £/ha	N saved £/ha	£/ha
1994	ARC	LNES	-0.53	-50	-53	15	-40
		LNLS	0.04	-20	4	6	8
1995	ARC	LNES	-0.49	-20	-49	6	-45
		LNLS	-0.23	0	-23	0	-25
1995	HM	HNES	-0.54	25	-54	-8	-64
		LNES	-1.20	15	-120	-5	-126
1995	RO	HNES	-0.83	-40	-83	12	-73
		LNES	-0.46	-60	-46	18	-30
1994	TR	HNES	0.33	60	33	-18	13
		LNES	-0.39	20	-39	-6	-47
1995	TR	HNES	-0.72	-70	-72	21	-53
		HNLS	-0.69	-60	-69	18	-53
		LNES	-0.08	10	-8	-3	-13
		LNLS	-0.06	40	-6	-12	-20
	1994 Mean		**-0.14**	**2.50**	**-13.75**	**-0.75**	**-16.50**
	1995 Mean		**-0.53**	**-16.00**	**-53.00**	**4.70**	**-50.20**
	Overall mean		**-0.42**	**-10.71**	**-41.79**	**3.14**	**-40.57**

Examination of the recovery of soil mineral N demonstrated that recovery can be predicted with accuracy and that an amount of N equivalent to the amount measured as ammonium and nitrate in early spring will be recovered by the time the canopy reaches maximum size. It therefore appears that the first component in the theoretical framework linking yield formation with N supply - the role of soil N - has a sound basis and has good potential to be used in commercially in winter wheat growing systems. Furthermore, the evidence for continued uptake of soil N well after flowering is important information having bearing on the production of grain for breadmaking. It may be that this continued uptake, particularly where soil mineral N amounts are large, can play a role in maintaining the canopy through to the end of grain-filling and obviate the need for late applications of N.

Analysis of the recovery of fertiliser N was encouraging. N uptake with Canopy Management was more consistent through the season; the rate of uptake was usually less than with conventional N but this more moderate uptake continued for longer during the grain filling period, which is consistent with the underlying philosophy of Canopy Management.

Furthermore, the values for apparent recovery and minimum rates of uptake found within these field tests on Mercia are consistent with our initial estimates of 60% and 2 kg/ha/day respectively. The recovery of the late applied N however, was disappointingly low and the reasons for this require further investigation.

Whilst the relationship between N uptake and canopy size was linear, Mercia required 26 kg N uptake to produce each hectare of canopy for a canopy of size GAI 5, and nearly 28 kg/ha N for a canopy of GAI 6. This was less than our initial estimate of 30, and is encouraging, because it provides the basis with which to relate a prescribed size of canopy to the amount of N uptake required. This then can be related to supply from soil and contribution from fertiliser N.

From our analyses of canopy size and light interception, our observations lead us to suggest that during the early phase of grain filling, the extinction coefficient (k) in Mercia is likely to be between 0.45 and 0.50 for total solar radiation and between 0.50 and 0.55 for PAR. The results here demonstrate that Beer's Law holds within Mercia wheat grown over a wide range of conditions and there is clearly little benefit to be gained in terms of light interception from increasing canopy size above GAI 6. Having demonstrated that the principle of Beer's Law applies to commercially grown winter wheat, it is now necessary to undertake more detailed measurements than were possible within this study to understand light interception in canopies in a more precise way, especially where there is a large proportion of dead material in the canopy, which may intercept light that would otherwise impinge on green tissues.

Data from this Project were subject to a parallel analysis as part of HGCA Project 0044/1/91, in order to improve understanding of crop growth in relation to weather and nitrogen. This analysis has shown that it may be better to quantify the photosynthetic capacity of the wheat canopy in terms of the nitrogen it contains rather than the area of its green surfaces. There would seem to be some logic in this since the amount of nitrogen in a leaf relates to the paleness of the leaf as well as to its area, and the paleness will also have a bearing on photosynthetic activity.

The results from our work on biomass production are less clear cut than expected. There was more variation in the efficiency with which crops converted radiation energy into biomass than was expected. Significant amounts of this variation could be attributed to seasonal differences, to differences in sowing date and to the effect of leaving crops without any fertiliser at all. It is important that despite these influences, the Canopy Management approach produced a similar level of efficiency (e) as the conventionally fertilised crops. Therefore, although the theoretical framework linking application of N to yield formation took e as being stable across a wide range of conditions, we have shown this not to be the case, and further work will be required to identify clearly how these changes come about. Since e was not affected by a change from conventional N management to Canopy Management we can conclude that this is not a basis for any difference in performance. However, the variability in e leaves us in some uncertainty about the amount of grain to expect from a given amount of intercepted light and therefore we are left with some uncertainty about the optimum level of N uptake or the optimum size of crop canopy to specify; from the present stage of analysis, it does appear that these will vary from season to season and according to date of sowing.

The analysis of biomass partitioning has shown that the Canopy Management approach generally reduced then amount of straw. This could be a marginal advantage where straw must be incorporated into the soil after harvest and before establishment of the succeeding crop. However, where straw is normally needed for associated livestock enterprises this may be a slight disadvantage.

Work by our group in parallel projects (especially HGCA Project 0037/1/91) has shown a benefit in maximising the quantities of stem material accumulated by wheat, since a considerable quantity of this is apparently remobilised during grain filling. Crops with particularly large reserves (distinguished according to variety) which encountered poor grain filling conditions (through drought) have been shown to be at a significant advantage over crops with smaller reserves. It may be that the smaller stem weight (per square metre) of Canopy Managed crops leaves them at a disadvantage when they subsequently encounter adverse grain filling conditions, as probably occurred in some of these experiments in 1995, and possibly also in 1994.

Although the adjustments in partitioning resulted in a slightly smaller amount of total biomass at the end of the season, the harvest indices were larger and there was a slightly improved yield of grain at harvest. It is interesting to consider the origin of this yield increase, since the theoretical analysis made at the outset did not lead us to anticipate that a yield increase would be possible. Two possibilities arise. Both relate to the decreased density of shoots created by Canopy Management. First, it may be possible that the increased illumination of lower leaves resulting from the sparser canopies gave rise to increased photosynthesis. Secondly, the greater illumination per shoot resulting from the sparser canopies may have been particularly effective during the phase of ear expansion when the 'sink capacity' per shoot tends to be set. Hence, crops may have been generally sink limited and this may have been marginally overcome in the sparser canopies.

It was somewhat surprising that the benefit from Canopy Management arose through limitation of maximum canopy size rather than prolongation of green area during the grain filling period. It is not only important to investigate further the reasons for the poor response from the late N on canopy duration but it is equally important to examine the precise reasons why more moderate canopies can produce yield advantages.

Although Canopy Management generally used less fertiliser N, it resulted in an overall increase in grain N and it is unlikely that Canopy Management will have a deleterious effects on the N aspects of breadmaking quality. It seems probable that the application of N at made flowering, although not being as important as was expected in maintaining canopy longevity and grain yield, was significant in ensuring that the quality of grain for breadmaking was not compromised.

Overall, the results of this Project are very encouraging because they demonstrate that the Canopy Management approach, derived entirely from a physiological understanding of crop processes, gave an improved financial benefit when compared to a conventional approach. There seems every reason to continue with the development of Canopy Management as a strategy not only for determining applications of N to wheat, but to extend these to other crops, particularly barley and oilseed rape. Also, is seems worth using this approach as a basis for reconsidering other aspects of crop management, particularly those which exert influences through their control over canopy size. In particular it would seem well worthwhile examining the adjustment of seed rate, in concert with the adjustment of fertiliser N.

Finally, and significantly, we have shown that N use can be effectively rationalised, through Canopy Management, based on the fundamental principle that a given quantity of N is essential to provide the photosynthetic machinery for full exploitation of available sunlight. Thus we have improved the justification for the Industry's dependence on fertiliser N.

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