



**RESEARCH REVIEW No. OS5**

**CROP NUTRITION AND  
FERTILISER REQUIREMENTS  
FOR THE DOUBLE LOW  
OILSEED RAPE CROP**

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1. ABSTRACT

The purpose of this review is to draw together the available information from the U.K. and internationally on the major and trace element requirements of oilseed rape, with particular reference to double low varieties. Topics which need further research are identified and appropriate studies are recommended.

Double low varieties of oilseed rape (Brassica napus), with low seed contents of both erucic acid and glucosinolates, are now grown almost exclusively in the U.K. Most information previously obtained on the fertiliser needs of single low varieties can also be applied to double low varieties, however there is recent evidence of different responses between the two types to certain nutrients. Although heavier textured soil types predominate, winter oilseed rape is now grown on a wide range of soils, including sandy soils which are more prone to give trace element deficiencies in arable and other crops. Apart from S, deficiencies of major nutrients are of less concern because of fertiliser inputs over many years, also organic manures where applied, which have raised the P and K reserves of most arable soils to a satisfactory status.

The area of spring-sown oilseed rape has to date been very small and mainly confined to those areas with soil types and climatic conditions which are more suited to spring cropping, particularly where the amount of pigeon damage during the winter would be unacceptable. Interest had revived in the spring crop because those

double low varieties can consistently achieve glucosinolate contents below 20  $\mu\text{mol}/\text{gram}$ , when EEC premium payments for harvested seed was based on seed glucosinolate content. The change in the EEC price structure including support payment on an area basis for oilseed rape, and resultant lower prices for rapeseed, has again focused attention on the spring-sown crop because of its lower input requirements including N and a gross margin comparable with the winter crop despite lower yields.

Each of the major and trace elements are discussed in respect of

- their role in plant nutrition
- deficiency symptoms and occurrence in oilseed rape
- crop requirement and effects of nutrient application on seed yield and quality
- type, rate and timing of fertiliser application for optimum yield or to either prevent or correct deficiencies.

Methods of predicting or diagnosing nutrient deficiencies, both from a knowledge of soil type characteristics and by using foliage or soil analysis, are also discussed for particular elements. Oilseed rape will tolerate a wide range of soil pHs, 6.5 to 7.0 is considered ideal for most mineral soils but pH 6.2 is recommended for light textured soils in Scotland.

The application of nutrients influences biomass production, but not the development stages of the plant, and N has the most important role. The amount of vegetative growth and subsequent branching of the oilseed rape plant increases with N application and greater biomass production during the growth period pre-flowering results in more pods per plant. This is the main component of yield which is responsible for yield responses to increasing amounts of N fertiliser, effects of N on seed size and seed weight are less consistent. Around 90% of the yield can however be obtained with only 60% of the optimum N rate, because of the very shallow but still economic yield responses obtained at the larger N rates. The application of N does not seem to influence the sequence of flower development but delays and prolongs the flowering period.

The effects of rate and timing of autumn and spring applications of N fertiliser on seed yield, oil and glucosinolate contents are discussed. Experimental evidence indicates that double low varieties have similar N requirements to previous, single low varieties of oilseed rape. The economics of applying autumn N are often marginal and possible factors which will reliably predict the chance of a unique yield response to autumn N are still poorly understood. Recent experiments have however identified straw disposal as one such factor. Prior to the change in the EEC price structure towards the end of 1991, autumn N at 50 kg N/ha had been recommended for winter oilseed rape in most situations. Similarly, spring N applications of 200 to 280 kg/ha for winter oilseed rape and 125 to 150 kg/ha for spring-sown crops were recommended as optimum rates after cereal cropping. Recommended rates of autumn and spring N have now been reduced as a result of the major drop in the price of rapeseed. At present, prediction of N requirement is usually based on empirical site factors, as direct measurement of the soil N supply is only more beneficial where the fertility is greater than usual. Timing of spring N fertiliser depends on the start of crop growth in the spring and the risk of leaching loss in different soil types. The appreciable residues of N left after oilseed rape and the need to take account of them when fertilising the following crop are discussed, also the use of urea as a suitable alternative to ammonium nitrate for spring top dressings on winter oilseed rape. Nitrification or urease inhibitors, used in conjunction with urea, have not shown any advantage at normal timing of spring applications. Effects of plant growth regulators and irrigation, relative to N use, are also discussed.

Experimental evidence on the yield responses to P and K is summarised. Deficiencies of either nutrient are rare in the U.K., as most arable soils are well supplied with these nutrients, and yield responses to freshly applied have only been obtained in experiments where soil P or K-reserves are very low. Appropriate fertiliser strategies for P and K are discussed, in most situations only maintenance dressings are required to balance crop offtake of these nutrients in the seed at harvest. Seed quality is usually unaffected by P and K application.

The situations in which Mg deficiency may occur, and the possible need for application of Mg fertiliser to prevent or correct a deficiency are discussed. Oilseed rape is not very susceptible to Mg deficiency, which is most likely on sandy soils. The deficiency can however be induced on a wide range of soils if the soil or growing conditions put the crop under stress. The symptoms are often transient in such situations and treatment with a foliar spray of Mg is unlikely to increase yield. Maintenance of adequate Mg status in the soil for the overall arable rotation is advocated, to prevent a deficiency of Mg which could limit yield.

With the introduction of double low varieties and the decline in atmospheric S levels, S deficiency in oilseed rape is becoming more widespread in the U.K. Yield can be as much as trebled under conditions of severe S shortage but the seasonal expression of S deficiency varies according to the interaction between soil S supply and crop uptake. Plant S supply differs widely according to soil type and location and has a primary influence on seed glucosinolate concentration. This influence is still poorly understood and modified to a greater or lesser extent by other factors, notably the effect of N supply and season on crop structure. The efficacy with which the different forms of S fertilisers improve crop S status is known in principle but the optimum amounts and timings of these forms to maximise yield yet minimise glucosinolate content of rapeseed have not been precisely quantified.

There is very limited information on the trace element (B, Cu, Fe, Mn, Mo, Zn) status of oilseed rape grown in the U.K. Advisory experience indicates that deficiencies of trace elements generally are not limiting U.K. production of oilseed rape. However, deficiencies of boron and, to a lesser extent, manganese occur infrequently on sandy soils of alkaline pH and peaty soils in some seasons. Yield responses of up to 0.5 t/ha have been obtained from application of boron fertiliser but prediction of such yield responses has not been identified satisfactorily.



Recommendations are made for further studies on the efficiency of N recovery by the new varieties of oilseed rape with shorter growth habit under different conditions of crop structure as a result of emergence date and N application. Such studies, in conjunction with measurement of N residues left by the crop after different rates of N fertiliser application, would enable the development of an N balance model to determine N requirement of the crop more reliably. Studies are also proposed on examining the S status of U.K. crops to determine possible links with seed glucosinolate content at harvest, and the influence of site, soil, season and crop factors on glucosinolate content. Such studies would also identify the extent to which crops are becoming deficient in S. Further work is needed on both the behaviour of S in soil, the prediction of S deficiency and also the best strategy for applying S fertiliser.

Further studies on the trace element contents of oilseed rape on various soil types and the procedure for predicting boron deficiency, are recommended, also a more comprehensive review of the physiology of oilseed rape.

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## 2. GLOSSARY OF TERMS

- Acropetally - development of organs in succession towards the apex, oldest at the base and youngest at the top.
- Apical meristem - the apex of growing point of the plant, which initiates leaf and flower bud formation.
- Bract - a modified leaf, growing at the base of a flower or on its stalk.
- Genotype - a genetically distinct variety.
- Harvest Index - the weight of seed as a percentage of the total above ground dry matter per unit of the crop at harvest maturity.
- MAFF - Ministry of Agriculture, Fisheries and Food.
- Mineralisation - the microbial production of mineral nitrogen (nitrate- and ammonium-N) from organic nitrogen.
- Ontogenesis - the development of an organism throughout its life.
- Pedice! - a flower stalk within an inflorescence.
- Peduncle - the stalk of a flower.
- Petiole - the leaf stalk.
- Primordia - initial points of development for leaf and flower buds.

- Raceme - a cluster of flowers with individual flowers growing on small stems at intervals along one central stem.
- Soil Mineral N - the content of ammonium- and nitrate-N in the soil to a specified depth.
- Soil Type - the physical characteristics of a soil profile in terms of texture, depth, stoniness and drainage status.
- Vernalisation - the stimulation of reproductive, as well as vegetative growth by exposure to low temperature.

### 3. INTRODUCTION

The area of oilseed rape grown in the United Kingdom (U.K.) has increased considerably over the last twenty years to an estimated 452,000 hectares in 1990 (MAFF, 1991). So far only a small proportion of the total crop area has been sown to spring varieties since autumn sowings of winter varieties usually have a large yield advantage, especially in drought years, and seed oil contents tend to be slightly higher. Also many heavier textured soils, on which oilseed rape has commonly been grown, are poorly suited to spring cropping. However where pigeon damage would cause severe problems during the winter, if feasible, spring varieties are used instead.

In terms of area, oilseed rape is the most important arable break crop within the U.K. The benefits of its inclusion within the rotation, including increased residual N fertility and weed and disease control as well as higher yield in the following winter wheat crop, are discussed by Almond et al. (1986). Oilseed rape will tolerate a wide range of soils, the suitability and limitations of different soil types have been reviewed by Archer (1981). Although the crop is widely grown within the U.K., Bowerman et al. (1990) identified Eastern England, the East Midlands and to a lesser extent Eastern Scotland as the major areas of production and clay soils as the predominant soil type for growing rape.

Although rape cropping is concentrated on heavier soils, a significant proportion of the crop is also grown on coarser textured soils where the risk of trace element deficiencies are greater (Table 1).

Table 1. Soil type and frequency of growing oilseed rape

Topsoil texture	<u>Cropping density</u>	
	High <sup>1</sup>	Low <sup>2</sup>
	% rape area	
Sands and light loams	16	28
Medium loams	30	37
Clays	54	35

<sup>1</sup> 600-1700 ha per 10,000 ha      <sup>2</sup> 400-600 ha per 10,000 ha

Source: Bowerman et al. (1990)

Early, uniform establishment is important for winter oilseed rape in order to develop a good root system before the onset of cold weather. A fine, firm seedbed, combined with shallow sowing into moisture is necessary for quick germination and even emergence (MAFF, 1983a). Soil type, straw and trash residues and prevailing soil and weather conditions will therefore influence cultivation requirements each season. The tap root of rape plants is sensitive to soil compaction, which can seriously reduce growth and hence the efficiency of fertiliser use. Oilseed rape will tolerate a wide range of soil pH up to 8.0 in naturally calcareous soils. However crop growth is likely to be restricted on mineral soils below pH 5.6 (MAFF, 1981). The ideal range of soil pH is 6.5 to 7.0 on mineral soils, although 6.2 is recommended in Scotland for lighter textured soils from loamy sand to silt loam (A.H. Sinclair, pers. comm.).

Application rates of nitrogen (N) to oilseed rape in England and Wales have shown a substantial increase over the past twenty five years and, more recently, some decline (Table 2). The drop in N use since 1985 is mainly associated with reductions in autumn use of compound N fertiliser, only about half of the crop area received autumn N in 1989/90. There has also been a small decrease in the

rate of spring N fertiliser applied in straight form (Chalmers et al., 1991). However changes in phosphate and potash fertiliser rates have been relatively small.

Table 2. Overall fertiliser use on oilseed rape in England and Wales, 1975-90

Nutrient	1975	1980	1985	1986	1987	1988	1989	1990
kg/ha								
Total N	193	254	272	261	264	244	231	227
P <sub>2</sub> O <sub>5</sub>	53	51	58	62	59	59	52	51
K <sub>2</sub> O	49	38	55	56	54	59	49	55

Source: Chalmers et al. (1991)

The equivalent annual survey in Scotland, which started in 1983, has also shown similar recent trends in fertiliser use (Dyer et al., 1991). Current fertiliser use on oilseed rape in Britain costs about £36M and represents the largest variable cost in production of the crop.

Significant amounts of minor elements are applied to oilseed rape even though the likelihood of specific deficiencies is relatively small and depends mainly on soil type and, to a lesser extent, seasonal weather conditions. Both the English/Welsh and Scottish surveys collect information on minor or trace element usage on crops. Over the past five years, the proportion of oilseed rape in England and Wales treated with a foliar spray of one or more minor elements has varied from 13% up to 21%. Manganese was the most commonly applied minor nutrient, used on over half of the treated crop area, followed by boron and sulphur which were used on about one third of the crop area receiving foliar sprays (Table 3).

Table 3. Percentage of treated oilseed rape area receiving different minor elements as foliar sprays, 1990

Boron	Copper	Magnesium	Manganese	Sulphur
% treated area				
31	9	14	62	28

Source: Chalmers *et al.* (1991)

During the 1980s fertiliser recommendations were based on the results of field experiments with single low varieties containing less than 5% of erucic acid in the seed oil. Since 1987, commercial crop production has switched almost entirely to double low varieties in order to meet EEC quality standards for seed glucosinolate content. Double low varieties were initially lower yielding than the existing single low varieties, however breeding of new varieties has improved both oil yield and quality characteristics and also other agronomic features (Anon, 1991). Although much of the information available on the nutritional requirements of single low varieties may be extrapolated to double low types, there is some evidence that the two types may differ in response to certain nutrients. As a result, recent experimental work in the U.K. has concentrated on the effects of N and sulphur on the yield and seed quality of double low varieties. Although site and seasonal factors have a greater influence on seed glucosinolate content, possible nutritional effects, especially of sulphur (Milford & Evans, 1991), are also important in relation to current EEC requirements for glucosinolate contents of seed.

This review was undertaken to summarise the relevant information available from a wide range of commercial and research sources on the major and trace element requirements of double low oilseed rape, also to identify those topics which are considered to require further research and development and to recommend appropriate studies.

#### 4. NITROGEN

##### 4.1 Role in Plant Nutrition

Nitrogen is an essential constituent of all plant proteins and nucleic acids and consequently of all protoplasm (Wild, 1988). It can be taken up by plants either as ammonium or nitrate ions and is subsequently converted into amino acids, mainly in the green leaf. An increase in N supply causes greater leaf cell size and area, thereby providing a larger leaf area for photosynthetic activity. The net effect is to increase crop growth substantially as long as other factors are not limiting.

The oilseed rape crop has a large requirement for N and apart from exceptionally fertile sites, substantial amounts of N fertiliser are needed to supplement the soil N supply for optimum yield. Severe deficiency symptoms are rare and are usually associated with other factors such as waterlogging or poor straw incorporation. Leaves and stems turn light green in colour and leaf chlorosis, often with associated purpling, develops subsequently. Crop growth is severely restricted where N deficiency is acute, with less branching, fewer pods and more restricted flowering leading to premature seed ripening.

Use of N fertiliser often increases yield by at least 100% under U.K. conditions and is the most important agronomic factor in determining yield level. The degree of yield response varies principally with soil type and N fertility, consequently these site factors determine the optimum rate of fertiliser N. Most of the economic yield increase is achieved with 50-75% of the N requirement, followed by a much shallower yield response up to the optimum N rate (Fig. 3). Increasing rates of N fertiliser increase crop propensity to both lodging, which can limit yield when it occurs early in the season (Ogilvy, 1985) and infection by foliar diseases (Darby & Hewitt, 1990). An interaction between use of seedbed N, greater incidence of stem canker and subsequent lodging has also been observed (P. A. Johnson, pers. comm.) although such interactive effects will



partly depend on varietal susceptibility. Correct timing of N can also influence yield, particularly for winter rape with its long growing season, as well as minimising potential leaching losses of nitrate.

## 4.2 Crop physiology and N effects on growth and yield components

### 4.2.1 General

During the course of the growing season the oilseed rape plant progresses through a sequence of well defined vegetative and floral stages that lead to the production of leaves, stems, and floral structures called racemes. Although the terms crop growth and crop development are frequently used synonymously they are, nevertheless, very distinct physiological processes that progress in parallel, but sometimes at different and unrelated rates. Growth refers to an increase in size or weight; development refers to the series of changes in plant form during the period from sowing to maturity.

Four main phases of growth (Fig. 1) can be identified according to key developmental events:

- (a) pre-floral vegetative growth
- (b) floral initiation and hierarchical bud development
- (c) flowering
- (d) post-flowering growth.

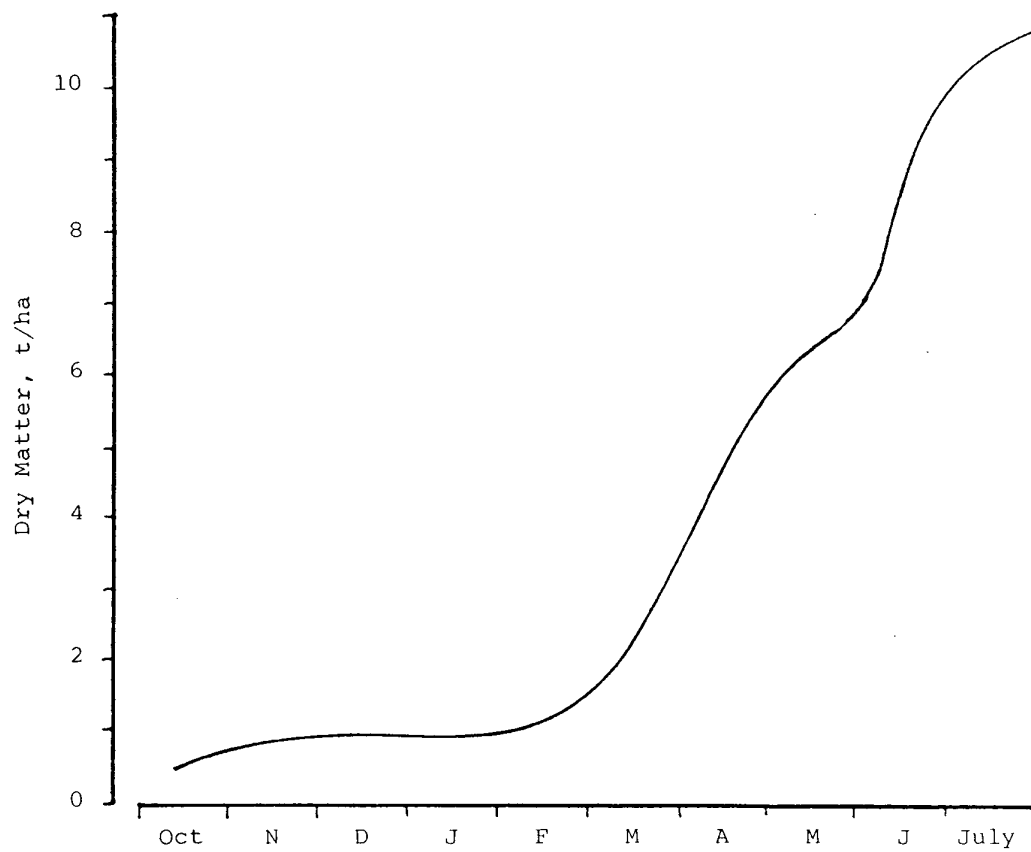
These successive changes between vegetative, flowering and pod canopies are largely determined by seasonal changes in temperature, day-length and radiation inputs. Nitrogen does not influence the initiation and progress of these developmental changes, but has a key role in regulating growth, thereby influencing the amount of assimilate that is available for the production and survival of the different components of yield.

Fig. 1. Development and growth of winter oilseed rape

(a) Development



(b) Dry matter production



#### 4.2.2 Pre-floral vegetative growth

The central feature of pre-floral vegetative growth is the initiation of leaf primordia and their subsequent emergence and expansion to form the crop canopy. The potential size of this canopy for a given plant population is determined by the number of leaves produced and the size of individual leaves.

##### Initial crop establishment

This is primarily influenced by the physical conditions of the seedbed together with the prevailing soil moisture and temperature conditions (Daniels & Scarisbrick, 1983), although a soil deficiency for example of phosphorus can also affect establishment. Nitrogen does not have a direct effect on seedling emergence, unless the fertiliser is placed too close to the seed which can reduce emergence, especially in dry soils (Holmes, 1980).

##### Leaf initiation

During the early stages of germination, the radicle emerges from the imbibed seed followed by the aerial extension of the cotyledons, whose oil reserves support this early growth (Daniels & Scarisbrick, 1983). Leaf primordia are subsequently initiated at the periphery of the promeristem on the shoot apex which is already present between the cotyledons. This process is continuous between germination and the start of flower initiation when up to 27 main shoot leaves can be initiated (Scarisbrick & Daniels, 1984). The rate of leaf initiation is dependent upon carbon supply to the site of production and is therefore predominantly influenced by temperature and radiation, although both Scott et al. (1973a) and Mendham et al. (1981b) found that leaf initiation increased with increasing amounts of seedbed N.

## Leaf appearance

Following the differentiation of primordia, individual leaves maintain a continuous pattern of development with no clear physiological event that can be adopted as definitive. Leaf appearance rates are determined by the rate of cell division and expansion of the stem apex. Despite the dramatic visible effects of N on leaf appearance, the mechanism underlying these processes are not well understood.

## Leaf expansion

Leaf size is influenced by:

- (a) the number of cells in the primordia
- (b) the rate and duration of cell division
- (c) the size of the mature cells

The potential size of a leaf is determined by cell number but it is cell expansion which eventually determines final leaf area. N supply affects cell size but temperature and radiation are the main factors influencing the rate of leaf expansion. From primordial initiation until well into the unfolding phase, leaf growth is dependent on an assimilate supply from other parts of the plant and rapid development and ramification of the vascular network is essential during this period.

There is very little information available on individual leaf growth patterns in oilseed rape. Sylvester-Bradley & Makepeace (1984) describe leaf growth in their development code and although leaves are coded in an identical manner, emphasis is placed on the different leaf ontogenesis. During the rosette stage of growth, which extends from the beginning of leaf production until the first node becomes detectable, leaves are classed as petiolar. These leaves possess a petiole which is clearly visible between the leaf laminar and stem. As the stem extends, however, ontogeny changes petioles are either

greatly reduced or absent, giving rise to sessile leaves whose lobes clasp the stem.

### **Stem growth**

In winter oilseed rape the stem accounts for a very small part of the total crop biomass until growth recommences in the spring.

Thereafter, internode length increases rapidly (Scarisbrick & Daniels, 1984). In addition to providing a structural role the stem is photosynthetically active and has a storage function (Evans, 1984). Remobilized stem reserves make an important contribution to seed growth during the early pod growth phase. Autumn applied N has a direct effect on stem dry matter, leading to increased plant height in early winter (Harris, 1980). In spring oilseed rape Allen & Morgan (1972) showed that increased N application encourages branching from the proximal nodes of the stem. Similar results have been recorded by Leach et al. (1989) for winter oilseed rape.

### **Crop canopy**

In oilseed rape, like other temperate crops, dry matter accumulation and crop yields are determined more by how much light the crop canopy can capture than by the intrinsic photosynthetic activity of the leaves themselves. However the correlation between seed yield and leaf number in oilseed rape is very low (Campbell & Kondra, 1978). Leaf emergence is initially rapid and provides full ground cover before the onset of winter. Seedbed N stimulates dry matter production during this period, although excessive vegetative growth is not always associated with increased seed yield (Islam, 1987).

An increasing N supply increases leaf area index (LAI) during the spring in both winter and spring oilseed rape (Allen & Morgan, 1972; Scott et al., 1973a; Islam, 1987). Scott et al. (1973a) in experiments with the winter sown variety Victor recorded maximum LAI values of between 3.5 and 4.0 with 300 kg N/ha, compared to values of between 3.0 and 3.5 with 200 kg N/ha. The extra leaf area did not however produce an increase in seed yield.

#### 4.2.3 Floral initiation and hierarchical bud development

Flower initiation marks the onset of reproductive development and is characterised by the apical meristem being induced to initiate flower primordia in place of leaf primordia. The number of leaves, other than bracts, is fixed at this stage and the size of the leaf canopy will therefore be determined within the limits which may exist for individual leaf size. Evans & Ludeke (1987) have shown that for winter oilseed rape the maximum leaf number produced in any one variety is smaller for late sown crops, while Mendham *et al.* (1981a) suggests that flower initiation will not occur until a minimum number of 12 leaves have been differentiated. Mendham & Scott (1975) however proposed that an inadequate crop framework is produced and yield potential is reduced if a critical plant size is not reached before the requirement for floral initiation has been fulfilled. Jenkins & Leitch (1986) however showed that late sown crops with smaller leaf numbers can produce high yields, provided that the onset of spring is early.

Flower initiation is primarily determined by genetic constitution, but is also influenced by day-length and temperature. In winter oilseed rape, Tommey & Evans (1991) have shown that temperature has a greater influence on flower initiation than day-length, while the vernalisation requirement of field grown crops appear to be adequately fulfilled if sown at the optimum time. Daniels & Scarisbrick (1983) maintain that for crops sown in late August to early September this switch to reproductive growth will generally occur in November. For crops sown in mid-October flower initiation may be delayed until January, although the effects of sowing date will be modified by genotype (Evans & Ludeke, 1987).

The N status of the plant does not appear to have a significant influence on flower initiation, although Vince-Prue (1975) maintains that for vernalisation to be successfully completed, an adequate supply of carbohydrate is necessary. Recent experiments at Boxworth Experiment Centre have however shown some yield benefit from partial crop defoliation in late winter (L.V. Vaidyanathan, *pers. comm.*).

The first reproductive parts to develop are those on the terminal raceme followed sequentially by the primary branches which are produced in a characteristic phyllotatic spiral. Within each branch and the terminal raceme the floral initials develop acropetally and those at the base are therefore developmentally more advanced, resulting in an indeterminate growth habit. The early superiority of these basal initials is strengthened as growth and development continues because of their favourable position relative to the supply of water and nutrients (Daniels et al., 1984). There is no evidence that N supply will modify this developmental sequence.

The pattern of hierarchical development in oilseed rape has been shown by Tayo & Morgan (1975) to persist through to maturity, although it can be modified by pest and disease attacks. Mendham et al. (1981a) maintain that the number of axillary inflorescences in winter oilseed rape is directly correlated with plant size at flower initiation. This may suggest that plant N status during early reproductive development may be one factor which influences the plant's hierarchical structure.

Analysis of yield components in oilseed rape suggests that the productivity of primary branches decreases with depth in the canopy (Daniels & Scarisbrick, 1983). To promote yield it may be desirable to suppress the production of the lowermost branches whilst increasing the dominance of the terminal raceme and the uppermost four axillary branches. Daniels et al. (1983) observed that seed yields were similar from plants supporting no branches to those supporting 5.5 branches per plant, indicating little correlation between branching and crop yield.

Axillary branch development is strongly influenced by N application. For spring oilseed rape, Allen & Morgan (1972) demonstrated that despite a high seed rate, branch number was greater when N supply was increased. Islam (1987) found a similar effect when the N rate was increased from 100 to 200 kg N/ha, although there was no response to N timing.

#### 4.2.4 Flowering

During the early part of stem extension, flower buds remain enclosed within the leaf rosette but as stem and peduncle elongation proceeds, the developing inflorescences emerge and become visible above the surrounding leaves (Sylvester-Bradley & Makepeace, 1984). The racemes of oilseed rape are indeterminate and this leads to a wide spread of maturity, which is detrimental to the achievement of consistent high yields. The first flowers generally open towards the end of April, but this varies from one season to another (Scarisbrick *et al.*, 1989) and within any one season, depending on sowing date (Evans & Ludeke, 1987). Flowering normally persists for four to six weeks, although the length of the flowering period differs between cultivars.

Increasing the rate of N results in a delay in flowering of between a few days (Holmes, 1980) and one week (Bunting, 1969) and also produces a greater number of open flowers due to a prolonged flowering period (Almond *et al.*, 1986). Allen & Morgan (1972) and Morgan (1981) observed that this increase in flower number was associated with a larger leaf area which probably increased the supply of carbon assimilates to the inflorescences. Evans (1985) and Dawkins (1985) in parallel studies found that N rates ranging from 100 to 350 kg/ha did not influence the number of flowers opening during the early phase of flowering but, during the later stages, high N rates produced significantly more flowers.

The highly reflective canopy of yellow petals leads to extremely inefficient use of incident radiation (Yates & Steven, 1987). Up to 60% of incoming solar radiation is reflected or absorbed by the floral canopy (Mendham *et al.*, 1981a). Light reaching the lower parts of the canopy at this time is dramatically diminished. Late applications of N may delay leaf senescence, provided adequate moisture is available (Islam, 1987).



#### 4.2.5 Post-flowering growth

At the end of flowering the oilseed rape plant is made up of a mainstem dominant terminal raceme and a number of primary branches. On all branches flower production exceeds pod production and Mendham & Scott (1975) found levels of flower and pod abortion of the order of 65% throughout flowering and subsequent pod development. This reduction in yield potential has mainly been attributed to a shortage of assimilates during critical stages of development, because of shading or reflection of light (Bilsborrow & Norton, 1984).

Daniels (1985), Dawkins (1985) and Evans (1985) jointly examined the effect of N on flower production and pod survival in an ICI funded project at the Universities of London, Nottingham and Newcastle. Increasing N rate from 100 to 350 kg/ha resulted in an increase in both the potential and fertile pod sites as a result of prolonged flowering on the lower order branches. Pod abortion rates in low and high N treatments were very similar. Splitting the N dressing to provide a larger N input early in the season increased pod abortion compared with the application of only 50 kg N/ha in late February (Evans, 1985).

Components of final seed yield in an individual rape plant are the number of pods, mean seed numbers per pod and mean seed weight (Daniels & Scarisbrick, 1983), of these the number of pods has the greatest influence on yield (Mendham et al., 1984). Within the crop, pod number per metre square is a very useful physiological parameter (Mendham et al., 1981a) which can be sub-divided further into plant number per metre square, branches per plant and pods per branch.

Pod growth occurs following fertilisation, but pod survival and seed number per pod are determined within a period of three weeks from full flower (Mendham et al., 1981a). Developing seed compete with the rapidly expanding pod wall during this critical phase for pod survival, just after flowering. Bilsborrow & Norton (1984) showed that a crop attains maximum pod canopy, which itself is photosynthetically active, at a time when the leaf area index is

reduced to 10% of its peak. However, early pod growth is dependant on current assimilates supplied by this declining leaf canopy.

The final phase of yield formation is seed production, which includes the determination of seed number and seed weight. Leterme (1985) suggested that seed number is determined shortly after fertilisation whereas seed dry matter accumulation is more dependant upon pod photosynthesis. Nitrogen has been shown to have a variable effect although increasing N rate has frequently resulted in a decrease in seed number per plant (Scott *et al.*, 1973a; Dawkins, 1985; Evans, 1985; Islam, 1987).

The major source of assimilates for seed growth is provided by pod photosynthesis during the post flowering period (Brar & Thies, 1977; Bilsborrow & Norton, 1984) but the possibility of carbon remobilisation by stems and roots cannot be ruled out (Evans, 1984; Chapman *et al.*, 1984). Maintaining a high plant N status during the period of pod growth could therefore be expected to increase seed weight. This has not been critically examined although Islam (1987) found that seed weight was significantly increased by delaying N application until the start of flowering where soil moisture was not a limiting factor in N uptake.

#### 4.3 N Uptake and Removal

The amount of N taken up by winter rape during the autumn varies considerably and mainly depends on date of emergence, use of autumn N fertiliser and the subsequent length of time available for growth before the onset of winter stops further growth. Crops emerging in August may on average contain 80 kg N/ha by the end of November whereas crops emerging a month later will often contain less than half this amount, with most of the N contained in the leaves. This effect is well illustrated in data from Rothamsted multi-disciplinary trials (Table 4), which also showed that early sown oilseed rape was particularly effective in utilising high soil N residues at the 1988/89 site which had been ploughed out of permanent grass three years previously.

Table 4. Mineral N content of the soil in mid-September and crop uptake of N

Season	Soil Mineral N <sup>1</sup>	Crop N uptake			
		Nov/Dec		Feb/Mar	
		Early <sup>2</sup> sown	Later <sup>3</sup> sown	Early sown	Later sown
	kg N/ha				
1984-85	192	96	28	89	57
1985-86	134	34	14	46	22
1986-87	119	63	38	78	52
1987-88	185	40	15	68	40
1988-89	337	150	25	170	95

<sup>1</sup> 0-90 cm depth, includes seedbed N residue

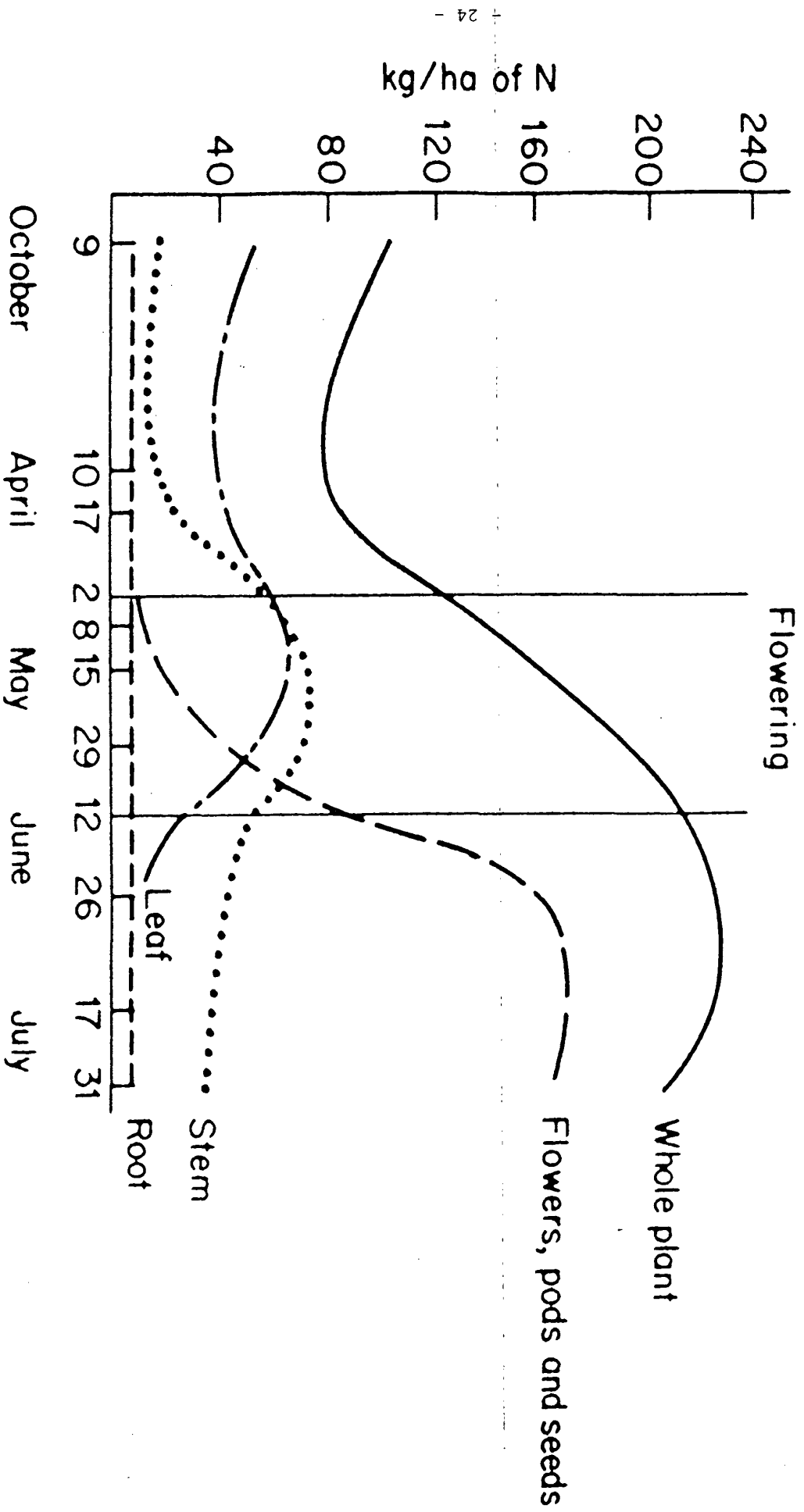
<sup>2</sup> Mid-August                      <sup>3</sup> Three weeks later

Source: Anon (1986a; 1987a; 1988; 1989a; 1990a)

The potential benefit of winter oilseed rape as a cover crop, to limit nitrate leaching losses overwinter, has been studied recently by Jensen (1989), Muller *et al.* (1989) and Shepherd (1990). Crops may lose some older leaves over winter, due to frost or bird damage, this reduces the total N content in the crop during this period.

The main and rapid phase of N uptake is during spring growth from early April to mid June, usually with a small increase during flowering (Holmes, 1980). Earlier studies showed that most crops reach a maximum uptake in June of 200-250 kg N/ha at about the end of flowering, depending on the amount of dry matter production (Holmes, 1980). Barraclough (1989) however found a maximum uptake of 364 kg N/ha by a high yielding (5 t/ha) crop. Total N content then declines as the crop ripens by which time most of the N is present in the pods and seeds and leaf loss has occurred (Fig. 2). Spring rape also shows a sigmoidal pattern of total N uptake, with the highest rate of uptake in the pre-flowering period. Total N uptake is however less than in winter rape due to lower dry matter production (Allen & Morgan, 1972).

Fig. 2. Pattern of nitrogen uptake by winter oilseed rape



Source : Holmes (1980)

The average amount of N removed in the seed is 33 kg/tonne for winter rape, both for single low (Holmes & Ainsley, 1978) and double low varieties (Chalmers, 1991) and 37 kg/tonne for spring rape (Holmes & Ainsley, 1977). Consequently even high yielding crops used to leave substantial N residues in the soil, of which a significant amount was present in mineral form in late autumn, particularly if the crop had received more than the optimum rate of N for yield (Sylvester-Bradley, 1991). For winter oilseed rape the apparent recovery of N fertiliser in the seed at harvest is approximately 25-35% compared with a range of 43 to 88% for winter wheat (Bloom et al., 1988).

#### 4.4 Autumn N for Winter Oilseed Rape

##### 4.4.1 Plant size and winter hardiness

Scott et al., (1973b) emphasised the importance of achieving an adequate plant size during the autumn growth period before inflorescence initiation occurs, so that the eventual size of the inflorescence is not limited. Autumn applications of N can at least double the amount of plant dry matter produced in the autumn by increases in leaf area and plant size, however very forward growth at this stage increases crop susceptibility to frost damage or winter kill (Andersson et al., 1956; Pieczka, 1969; Voskerusa, 1975; S. Ogilvy, pers. comm.). This effect of N on winter-hardiness is however only a significant factor in severe winter climates or exceptional seasonal weather conditions and moderate applications of autumn N normally do not affect plant survival over winter in the U.K.

##### 4.4.2 Yield response to autumn N

Several series of experiments in the U.K. have investigated the effects of autumn N on the yield of winter oilseed rape. Holmes and Ainsley (1978) tested four seedbed N rates with 130 or 200 kg/ha spring N (Table 5).

Table 5. Mean effect of seedbed N on yield at 200 kg/ha spring N across 33 sites

0	35	70	105
t/ha (90% DM)			
2.71	2.79	2.89	2.88

Source: Holmes & Ainsley (1978)

The results indicated an overall economic response to about 60 kg/ha seedbed N, with eight of the thirty three sites showing significant yield increases. Seedbed N have was considered to have increased the yield potential irrespective of the amount of spring N applied, although only two spring rates were tested. Possible varietal differences in N response were not examined in that series of experiments, however other trials work at that time did not show any difference between high and low erucic acid cultivars in seedbed N requirement (Ainsley, 1977).

Experiments by the Agricultural Development and Advisory Service (ADAS) in the 1970s showed no overall yield benefit from seedbed N over twenty eight sites (Archer, 1985) so that on average seedbed N use was not economic and did not apparently affect the response to spring top dressing. Eight sites did however give yield responses large enough to cover the cost of seedbed N fertiliser. These responses were related to yield level (Table 6) with higher yielding sites being most likely to respond. Soil type was not an important factor.

Table 6. Effect of winter oilseed rape yield on response to seedbed N

Yield level, t/ha (92% DM)	Number of sites	Number responding to seedbed N
<2.5	8	0
2.5-3.5	12	2
>3.5	8	6

Source: Archer (1985)

On responsive sites, yield increases were obtained with up to 50 kg/ha seedbed N. This rate was subsequently recommended for field crops (MAFF, 1983), although the yield benefit in the trials was small and largely unpredictable at the time of N application. Autumn N provided some insurance for good establishment by increasing early plant size and root development, also by reducing the risk of pigeon damage over winter because of better ground cover. In recent years however there has been a consistent reduction in autumn N use in England and Wales (Chalmers et al., 1991), whereas in Scotland virtually all crops still receive some autumn N.

Between 1982 and 1986, seventeen sites testing seedbed N rates from 0 to 105 kg/ha gave mean yield responses which increased with increasing N rate up to 0.1 t/ha at 70 kg N/ha (Paulson, 1988). Some sites though showed no significant responses to seedbed N. This variation was unrelated to factors normally associated with a high soil N status. The use of only one level of spring applied N did not give the opportunity to distinguish between unique responses to seedbed N and a response which could have been achieved with more N applied in spring.

Although the majority of the winter crop is grown on heavier textured soils, shallow chalk soils feature prominently in some areas and data for this latter soil type have been obtained at two ADAS Experimental Centres (ECs). Experiments at Bridgets EC in 1975-77 showed that seedbed N increased plant height slightly but had little effect on the yield of early to mid-September sown crops (Harris, 1980). Subsequent trials between 1983 and 1985, testing nil and 50 kg/ha autumn N gave similar results, site yields were however well below average in two of the years.

Several different trial series at High Mowthorpe EC examined effects of autumn N (Ogilvy, 1985). Initial trials in 1977-79, testing different combinations autumn and spring N rates, on average showed no yield benefit over the three year period from autumn N, even at the smallest rate of spring N tested (75 kg/ha). An economic response, up to 0.12 t/ha at 80 kg/ha seedbed N, was however obtained

in 1979. Subsequent trials in 1980-82 on seed rate and seedbed N showed no effect of N on yield although it slightly reduced the survival of plants overwinter. Further experiments in 1982 and 1983 with a range of seedbed and spring N treatment combinations gave no response to seedbed N in 1982. However in the 1983 season a mild open winter prolonged the autumn growth period and 50 kg/ha seedbed N increased plant size and vigour for the rest of the season, resulting in a significant yield increase of 0.2 t/ha. Further trials in 1984-86 looked at the effects of different rates and timings of autumn N on root and shoot growth, crop development and yield (S. Ogilvy, pers. comm.). Top dressing with autumn N produced "softer", more frost - susceptible crops, again there was no yield benefit from autumn N application.

Further ADAS experiments with double low varieties in 1988-90 tested a wide range of seedbed and spring N treatment combinations on medium and heavy textured soil types at twenty five sites (Chalmers, 1989; 1991). Spring N optima for yield data averaged across sites decreased with increasing rate of seedbed N, giving seedbed N efficiencies relative to spring applied N of 37, 47 and 33% respectively for the 30, 60 and 90 kg/ha rates (Table 7).

Table 7. Average optimum rate of spring N (Nopt) and associated yield (Yopt) according to seedbed N application, 1988-90 (25 sites)

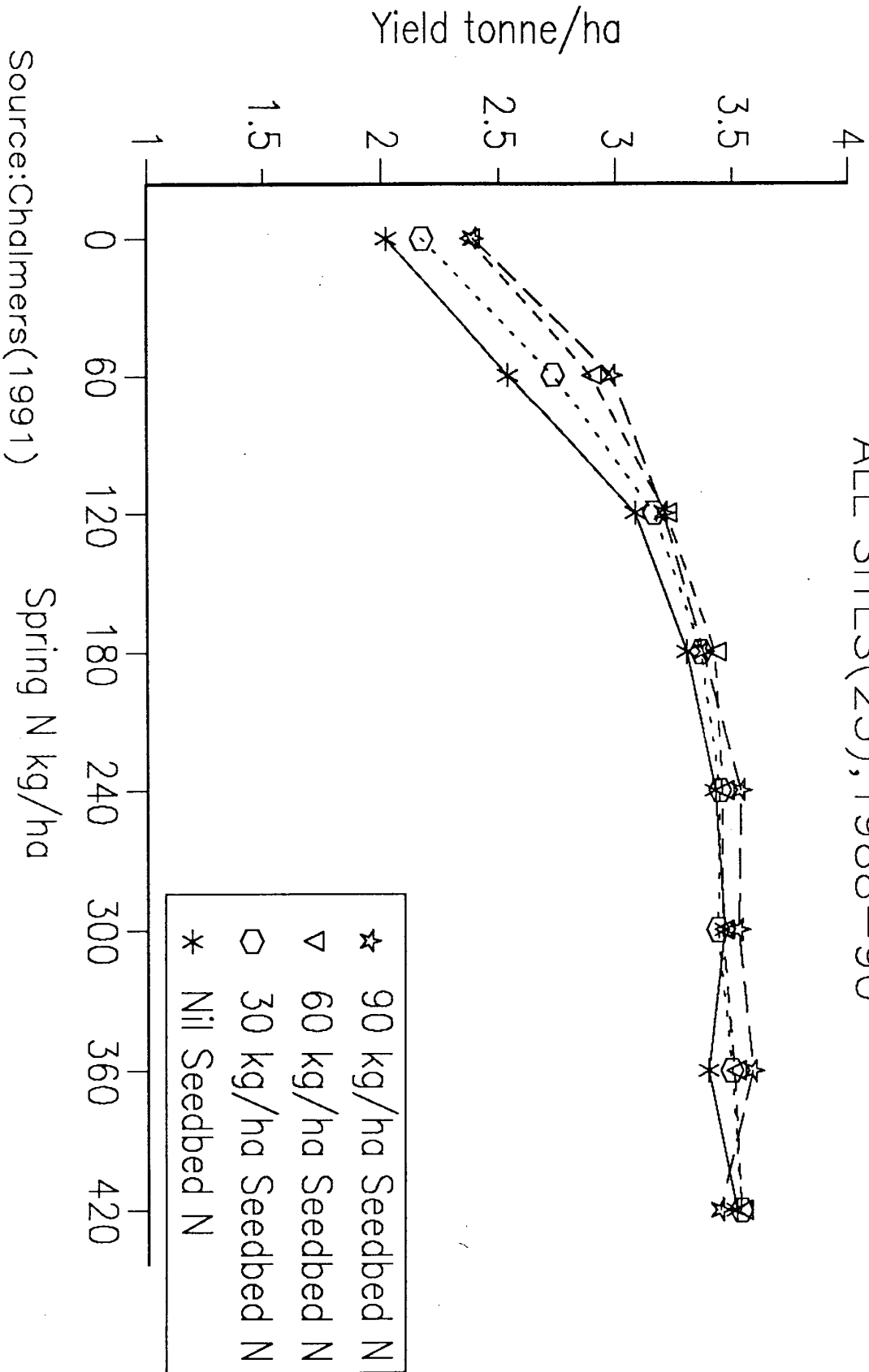
	Seedbed N, kg/ha			
	0	30	60	90
Nopt*, kg/ha	247	236	219	217
Yopt, t/ha	3.41	3.44	3.44	3.46

Source: Chalmers (1991)

\*at 1.3 kg seed: 1 kg N price ratio



Fig.3 NITROGEN FOR OILSEED RAPE--ADAS TRIALS  
ALL SITES(25), 1988-90



Application of seedbed N increased yield at sub-optimal rates of spring N (Fig. 3) but on average gave only a slight and uneconomic unique yield benefit at optimum spring rates. Ten sites however gave consistent economic yield responses over all seedbed N rates, mostly where straw was baled or incorporated rather than burnt and these effects were significant at six of the sites. On the basis of these results and the new price structure for rapeseed, ADAS subsequently recommended nil seedbed N where straw from the preceding cereal crop is burnt, and 30 kg/ha seedbed N following stubble or straw incorporation, on medium and heavy textured soils.

In Scotland, experiments in harvest years 1986 to 1988 on N and fungicide treatments applied in the autumn, also combined with different seed rates in the second and third years, gave variable results (A.H. Sinclair pers. comm.). A consistent and statistically significant yield increase with autumn N only occurred in 1986, otherwise yield benefits from autumn N were slight except in 1987 where there was a significant interaction between fungicide and N application which increased average yield by up to 0.26 t/ha. The recommendation for winter crops grown in Scotland has been 25-50 kg/ha autumn N, applied by early October at the latest, for soils with low to moderate soil N status (Dyson & Sinclair, 1990).

Other, limited data on seedbed N effects are available from U.K. experiments testing different straw disposal techniques prior to sowing winter oilseed rape. Some of this information is summarised by Bowerman et al. (1990) on the establishment of oilseed rape in the presence of cereal straw in recent experiments at Boxworth EC on chalky boulder clay and at Rothamsted Experimental Station on clay with flints. In 1986/87 at Boxworth EC, an extra 40 kg/ha N applied in October had no effect on yield where rape seed was broadcast into the standing wheat crop. Rothamsted trials in 1986-89 on straw disposal by burning, chopping or baling tested nil and 50 kg/ha seedbed N but only one rate of spring N. Seedbed N gave a small non-significant increase in yield of 0.14 t/ha when averaged over both sowing dates in 1986 and significantly increased yield by 0.21 t/ha (6%) and 0.19 t/ha (10%) in 1987 and 1989 respectively, but had

no effect in 1988. In further trials in 1987-89, crop establishment by broadcasting rape seed into standing wheat, also tested nil and 50 kg/ha seedbed N. Seedbed N increased the average seed yield by 0.44 and 0.69 t/ha in 1987 and 1989 but reduced yield by 0.32 t/ha in 1988.

A straw disposal trial on shallow limestone soil showed an increase of 0.36 t/ha (9%) in yield with 50 kg/ha seedbed N where chopped straw was incorporated by tine and rotary cultivation but only slight responses where the straw was ploughed in or burnt (Anon, 1985a). A long term straw incorporation trial on a light loam site in Kincardineshire showed no benefit from autumn N application when cropped with winter oilseed rape in 1987/88, the fourth year of the experiment (A.H. Sinclair, pers. comm.). An experiment funded by the Home-Grown Cereals Authority in 1991 on two heavy land sites, testing four cultivation techniques in combination with several N treatments for the establishment of oilseed rape in the presence of straw, did not show any yield advantage from autumn N use (P. Bowerman, pers. comm.). One of two sites in Cambridgeshire which tested different straw disposal and autumn N treatments in 1990/91 did however give an average yield increase of 0.26 t/ha (7%) to 40 kg/ha autumn N, even though a standard rate of 288 kg N/ha was applied at that site in the spring (B. Chambers, pers. comm.). No yield benefit was obtained at the second site from the same rate of autumn N, which was not however applied until early November after prolonged dry conditions earlier in the autumn.

Experiments elsewhere in Europe have also investigated the effects of seedbed N on winter oilseed rape, Holmes (1980) summarised work done in Poland and Switzerland prior to 1970 which rarely showed any benefit, due mainly to soil type and winter rainfall factors. Contrasting results have been obtained elsewhere. In Denmark, trials during 1971-76 indicated no benefit from autumn N for normal sowing dates in mid-late August and satisfactory growing conditions; where however sowing was delayed by two weeks and straw had been ploughed in, there appeared to be some advantage from applying part of the N requirement in the autumn (Nordestgaard, 1977). Trials in France

however during 1980-83 (Pouzet et al., 1984) showed that autumn N benefitted early sowings more than late sowings and was used more efficiently by earlier sown crops. A similar interaction between seedbed N and sowing date on early growth was found by Mendham et al. (1981b), probably because low temperature limited potential growth response in later sowings. Trials on deep loamy soils in Belgium indicated that about half (75-90 kg/ha) of the N requirement should be applied at sowing (Delhay, 1980). Autumn N at 45-60 kg/ha was generally recommended in Holland except for early sown crops on soils with a large N fertility (Boer, 1975). Use of autumn N has also been advocated in Romania (Pop, 1984) and Germany (Moller & Makowski, 1977), where experiments during 1975-80 indicated that autumn applications of 40-60 kg N/ha were needed as part of the total N application (Franck & Becker, 1982).

Experimental evidence on the need for seedbed N is therefore conflicting, in part this is because even small increases in seed yield of less than 0.1 t/ha have, until now, been economic. In addition, some experiments have not included a sufficient range of both autumn and spring N rates to determine reliably the efficiency of autumn N use and the extent of any unique yield responses to seedbed N which could not be achieved by applying the equivalent total amount of N only in the spring.

#### 4.5 Spring N Requirement for Winter Oilseed Rape

##### 4.5.1 N Rate

Numerous experiments, including early studies by Scott et al. (1973a; 1973b), have confirmed the large N requirement of oilseed rape grown after cereal crops in the U.K. A series of trials at forty one sites in England and Scotland from 1973 to 1977 gave a mean requirement of about 230 kg/ha spring N (Table 8), excluding those sites where low yields and poor response to N were associated with lodging, drought or bird damage (Holmes & Ainsley, 1979).

Table 8. Mean effects of spring N fertiliser applied in early March on seed yield, 1973-77 (41 sites)

N rate, kg/ha			
0	90	180	270
t/ha (90% DM)			
1.64	2.39	2.80	2.90

Source: Holmes & Ainsley (1979)

A separate series of experiments at thirty six sites in the mid-1970s, gave typical overall yield responses of 4-8 kg seed per kg N applied from nil up to the economic optimum rate (Archer & Vaidyanathan, 1982). Nitrogen optima increased with yield level, irrespective of soil type (Table 9).

Table 9. Spring N optima and associated yield levels, ADAS trials

Seed yield at optimum N	Number of sites	Optimum N
t/ha (90% DM)		kg/ha
<2.5	6	140
2.5-3.5	18	196
>3.5	12	236

Source: Archer & Vaidyanathan (1982)

Spring N rates of 200 kg/ha, or 240 kg/ha for crops with a yield potential above 3.5 t/ha, were recommended as a result of these investigations (MAFF, 1983b).

Although most trials work has concentrated on medium and heavy textured soils, yield response data have also been obtained on shallow chalk soils. Spring N optima varied between 175 and 275 kg/ha N in experiments at Bridgets EC during 1975 to 1977, optimum yields between 2.2 and 3.0 t/ha (Harris, 1980). Seasonal variation in N optima between 1975 and 1983 at High Mowthorpe EC were related

to yield (Ogilvy, 1985); N optima were between 275-325 kg/ha in four seasons where crops yielded over 3.0 t/ha, yields were lower in other years and there was no yield increase above 225 kg N/ha. Crops were usually stiff-stemmed and relatively short, so lodging was not a significant problem where larger amounts of N were applied.

Further ADAS experiments were done on medium and heavy textured soils in the mid-1980s to examine spring N requirements. A trial series from 1984 to 1986 gave N optima ranging from about 160 to 280 kg/ha, with an overall average optimum of 240 kg N/ha and corresponding yield of 4.0 t/ha (Anon, 1989). Only two of nine sites had yields below 3.5 t/ha at the optimum N rate. A series of trials by Hydro Fertilizers at sixteen sites in 1985 to 1987 showed an average optimum N rate for all sites of 206 kg/ha, based on oil yield (Paulson, 1988). Seed yields were not quoted but this lower than expected optimum may have been due to poor harvesting conditions, particularly in 1987. Site variation in N optima could not be explained by soil type, rotational or varietal differences, season had a large effect on oil yield but little influence on N requirement. Experiments at Morley Research Centre with double low varieties from 1987 to 1989 showed similar N requirements to earlier, single low varieties (Palmer & Stevens, 1990). The series of experiments from 1988 to 1990 on autumn and spring N at twenty five sites again showed that the optimum total N requirement increased with yield level, average spring optima in the absence of seedbed N were 220 or 280 kg/ha N respectively for yield categories below or above 3.5 t/ha (Chalmers, 1991). The subsequent change in the price regime for oilseed rape reduced these spring optima by 50 kg N/ha and ADAS N recommendations were subsequently revised to take account of these reductions in economic optima. The overall results also indicated that seedbed N use, where appropriate, gave an efficiency of about 50% and that the recommended spring rate of N should be adjusted accordingly.

Levington Agriculture tested the spring N requirement of double low varieties in a series of experiments across ten sites from 1988 to 1991 and concluded that these varieties require similar amounts of N

to single low varieties (K. Chaney, pers. comm.). Experiments by ICI Fertilizers investigated spring N requirement according to variety during 1975-78 (four sites) or use of plant growth regulator in 1983 (three sites), a long term trial at Ropsley Research Centre in Lincolnshire also tested the N response of oilseed rape in a crop rotation with three cereals from 1978 to 1990 (R.L. Ralph, pers. comm.). These experiments, and ICI-funded work at Sutton Bonnington, Newcastle University and Wye College in 1984-86 on the influence of N rate and timing on the growth and yield components of oilseed rape, showed a similar range of N responses to results obtained by other workers during this period.

Usually experiments in Scotland have shown spring N optima of 200 to 240 kg/ha (A.H. Sinclair, pers. comm.). The standard recommendation for crops grown in Scotland has been 200 kg N/ha with appropriate adjustments according to rainfall factors (Dyson & Sinclair, 1990).

Nitrogen requirements for winter oilseed rape have also been investigated in field experiments in most other European countries, these experiments have shown broadly similar yield responses to spring N as found under U.K. conditions. In earlier work reviewed by Holmes (1980), yield response ranged from 6 to 11 kg seed per kg N applied with the largest rate of response estimated to represent a 40% recovery of applied N in the seed at harvest. It was noted though that many of the investigations did not include sufficiently high rates of N to cover the whole range of yield response.

In France, long term trials showed that 300 kg N/ha was required for average maximum yields of 3.7 t/ha, with reductions in harvest and N harvest indices at higher N rates as a result of increased vegetative growth (Triboi-Blondel, 1988). Experiments in 1982 suggested that the plant population at the end of winter was the main yield - determining factor in areas with a severe winter climate whereas soil type and structure were more important in areas with milder winters (Fabre & Crozat, 1985). The influence of N fertiliser rate, plant density and climate on N assimilation by oilseed rape were studied in more detail by Robelin & Triboi (1983). In Holland a

seasonal reduction in the rate of spring N was recommended if a large dressing of autumn N was followed by a dry winter, to allow for reduced nitrate leaching losses (Boer, 1975). 100-180 kg/ha spring N was normally recommended depending on soil type, N fertility status and also the stage of crop development and size of plant population in early spring.

Experiments in Denmark during the 1970s indicated little advantage from applying more than 200 kg N/ha in the spring (Nordestgaard, 1977). Subsequent trials in 1979-82 showed yield responses up to 300 kg N/ha, the highest N level tested, when averaged over sites but no estimates of N optima were given (Nordestgaard *et al.*, 1984). Work in Sweden identified some varieties of winter swede rape which performed better when given smaller rather than larger N rates (Olsson *et al.*, 1981), suggesting that future developments in plant breeding might improve the efficiency of N use by oilseed rape. Experiments in Germany during 1975-80 showed a total N requirement of 200-240 kg/ha, including 40-60 kg N/ha applied in the autumn, for a yield of 3.5 t/ha (Franck & Becker, 1982). Measurement of the mineral N content in the soil did not however improve the prediction of spring N requirements.

Early trials work in Switzerland during 1969-73 showed no yield benefit from N rates above 120 kg/ha and no interaction of N rate with sowing rate (Vulllioud, 1974). Nitrogen requirements have also been investigated in various experiments in Eastern Europe, some trials in Czechoslovakia and Romania however used only moderate levels of N (Voskerusa, 1979; Pop, 1984). Other experiments in Yugoslavia during 1979-81 and Poland from 1977 to 1980 gave optimum spring N rates around 200 kg/ha, although seed yields were about 3.2 and 2.1 t/ha respectively (Radenovic, 1987; Szmigiel, 1987). Variation in yield due to seasonal weather was as large as that caused by N rate in the Polish trials. Nitrogen response data for Hungarian trials were reported by Nemeth (1987; 1988).

The importance of N and sulphur (S) interactions in S deficient areas has been demonstrated both in Canada and Europe, including the U.K.



in more recent years (Janzen & Bettany, 1984a; Milford & Evans, 1991). An inadequate S supply will reduce the yield response to applied N and the interactive effects of N and S are discussed in a later chapter of this review.

#### 4.5.2 Prediction of N Requirement

At present in the U.K., the amount of fertiliser N needed in the spring is predicted empirically from previous cropping, as an estimate of low, moderate or high N fertility status in the soil (MAFF, 1988; Dyson & Sinclair, 1990). Yield potential, based on past average field yields or soil type characteristics, is also included in ADAS recommendations. Measurement of the mineral (ammonium plus nitrate) N content to a specified depth in the profile, to determine soil N supply, has only been tested to a limited extent for oilseed rape. This approach has not given any significant improvement in predicting fertiliser requirement where the crop is normally grown on a low-N status soil after cereals in arable rotations. It is however a useful technique for fertile sites, as shown in the Rothamsted multi-disciplinary trials (Table 4). In two seasons the autumn soil N supply was relatively low and the largest yields were obtained from 225-250 kg N/ha when the crop was sown early (mid-August) and from 50 kg/ha more when sown later in the first week of September. At an intermediate level of soil N, maximum yield was achieved in later sown crop from 225-250 kg N/ha and in the final season, where high N residues were found in the soil, the largest yields were obtained without N fertiliser when sown early and from 100 kg N/ha when sown later. There is little published information on this aspect of N prediction; Henry and MacDonald (1978) showed that the separation of irrigation experiments in Canada into three categories of soil nitrate-N content gave some significant differences in both seed yield, oil and also protein responses to N, however incremental differences between the soil test categories needed to be at least 30 kg nitrate-N/ha (0-60 cm depth) to be of practical value. Rood *et al.* (1984) summarised some earlier work which indicated that spring rape in Canada was unlikely to respond to N fertiliser where the measured soil nitrate-N content exceeded 100 kg/ha. Field trials

in Southern Australia showed that anaerobic ammonium-N (determined by a two week incubation technique) gave a better prediction of seed yield responses to applied N than any of the other measured soil variables (Lewis *et al.*, 1987).

#### 4.5.3 Timing of Spring N Fertiliser

Several series of experiments in the U.K. have tested the effects of timing, as well as rate, of spring N on the yield of winter rape. Early work compared a range of timings at one or more rates of N across forty one sites (Holmes & Ainsley, 1979), as summarised in Table 10.

Table 10. Mean effect of timing of spring N top dressing on seed yield, 1973-75

Year	Number of sites	Timing	Seed Yield, t/ha (90% DM)
1973 and 1975	13 <sup>1</sup>	Early March	2.62
		Early Mar + Mid April	2.59
1974 and 1975	13 <sup>1</sup>	Early March	3.18
		Feb + early March	3.15
1975 to 1977	10 <sup>2</sup>	Early March	2.67
		February	2.69
		Late March	2.69
		April	2.48
		Feb + early March	2.67
		Early + late March	2.69
		Early March + April	2.59
		Feb + late March	2.67

<sup>1</sup> Mean of 90, 180, 270 kg N/ha rates      <sup>2</sup> at 225 kg N/ha  
Split applications mostly 1/3:2/3, a few sites compared one or more  
 $\frac{1}{2}:\frac{1}{2}$  timing splits.  
Source: Holmes & Ainsley (1979)

Timing of N application between mid-February and late March had little influence on seed yield or oil content, but applying half or all the N in April at early bud stage tended to reduce yield. There was no advantage from splitting the N top dressing.

Similar effects were obtained by Archer & Vaidyanathan (1982) in a series of experiments at twenty three sites, using total N rates of 150 and 225 kg/ha. Early dressings were applied in late February to early March, with the later dressings being applied about four weeks later. There was no effect of soil type or locality on the best timing (Table 11).

Table 11. Effect of timing of N top dressing on yield of winter oilseed rape, ADAS experiments

Timing	Yield t/ha
All early	2.86
50 per cent early 50 per cent late	2.85
25 per cent early 75 per cent late	2.76

Source: Archer & Vaidyanathan (1982)

Trials on N timing at High Mowthorpe EC showed no difference between a single dressing in early March and a 1/3 early:2/3 late (late March to early April) in 1982, but a yield reduction of 8% resulted from the split timing in 1983 owing to poorer spring growth, especially where no autumn N had been applied (Ogilvy, 1985). A series of experiments on medium and heavy textured soils in 1984-86 showed no average differences in yield between single and early split dressings (Anon, 1989b). There was however less risk of nitrate leaching losses from very early N dressings on these soil types, relative to coarse textured or shallow soils (Table 12).

Table 12. Mean effect of spring N timing on seed yield, 1984-86  
(9 sites)

Single Early March	Split	
	Mid Jan + Early March	Mid Feb + Early March
t/ha (90% DM)		
3.88	3.87	3.89

Source: Anon (1989b)

Paulson (1988) also found no significant yield differences between single and split applications of 250 kg N/ha although an early split of 50 kg N/ha in early February tended to give the highest yields at some sites. Scottish trials, in which 240 kg N/ha was applied either all in March or April or as an equal split, showed that the split application increased average yield by 1-2% (Anon, 1987c).

Trials in Germany (Herrmann *et al.*, 1976; Franck & Becker, 1982) and Poland (Budzynski *et al.*, 1986) also showed no yield benefit from split applications, compared with a single early dressing, although lodging was sometimes reduced. Results were more variable in Czechoslovakia (Voskerusa, 1979) where split applications are often used (Vasak *et al.*, 1985).

Few U.K. experiments have tested the effects of late N applications at the start of flowering. Field trials from 1984 to 1986 showed that a split dressing at this stage increased seed yield, by improving the sink size, pod survival, seed numbers per pod and seed weight (Islam, 1988). Two sites which also tested a late split of 80 kg N/ha gave slight yield responses of 2-4% with this late timing (Anon, 1989b). The effectiveness of late N dressings is however very dependent on the soil moisture status during the flowering period. Under dry conditions delaying part of the total N application until this stage would reduce yield and increase the subsequent potential leaching loss of N due to poor crop uptake. Late N application can also cause uneven maturity (Delhaye, 1980).

#### 4.6 N for Spring Oilseed Rape

Trials data on the N requirement of spring oilseed rape is more limited than for winter rape. Several experiments investigated the effect of N on crop growth and yield components under U.K. conditions (Allen & Morgan, 1972; Scarisbrick et al. 1980), other trials showed optimum rates of 150 to 200 kg/ha for spring-sown oilseed rape (Helps, 1971; Scott et al., 1973a; Storey, 1975; Potts & Gardiner, 1980).

In a series of twenty six experiments, Holmes & Ainsley (1977) compared the effects of both rate and timing of N application on yield (Table 13). Responses were obtained at all but three of the sites.

Table 13. Mean effect of N rate and timing on yield and oil content of spring oilseed rape, 26 sites: 1973-75

N, kg/ha		Seed Yield	Seed Oil Content
Seedbed	Top-dressing		
		t/ha (91% DM)	% (DM basis)
0	0	1.20	39.7
70	0	1.51	39.5
140	0	1.72	39.1
210	0	1.78	38.7
70	70	1.76	38.8
70	140	1.85	38.3

Source: Holmes & Ainsley (1977)

Average N optima varied according to previous cropping, from 158 kg/ha after root crops to 203 kg/ha after cereals. Split applications of N only gave a slight yield advantage but reduced the potential risk of nitrate leaching if heavy rainfall had followed seedbed application.

More recent trials in the U.K. have shown that more newer varieties have similar requirement to the older varieties. Freer & Oglivvy (1989) obtained yield responses up to 200 kg N/ha with both the varieties cvs. Topas and Drakker when sown on two different dates. The application of N could not however compensate for the yield loss (on average 21%) caused by the later sowing date, three weeks after the first sowing at the end of March. A subsequent trial in 1990 (Anon, 1990b) of similar design but with only one variety, cv. Puma gave low and variable yields, mainly due to pollen beetle damage, but responded up to 150 kg N/ha.

Scottish trials from 1988 to 1990 compared the effect of N on the yield of both turnip rapes (B. campestris) and swede rapes (B. napus) (Walker, 1988a; 1990b; 1990c). Optimum N rates were largest in 1988, at about 125 kg/ha for turnip rape and 150 kg/ha for swede rape, but no yield response was obtained above the lowest rates tested in 1989 and 1990, which were 90 and 75 kg N/ha respectively.

Before the change in price structure, 150 kg N/ha was generally recommended in the U.K. for spring-sown oilseed rape grown on soils with low N status after cereal cropping. In Scotland, although this rate applied to swede rape, 125 kg/ha N was recommended for turnip rape (MAFF, 1988; Dyson & Sinclair, 1990). As a result of the large drop in rapeseed prices, recommended rates have been provisionally reduced by about 30 kg N/ha pending more detailed analysis of experimental data. All the N fertiliser can be applied to the seedbed or as an early post-emergence top dressing in most situations. However for sandy or shallow soils, early sowings or in dry seedbed conditions, no more than 50 kg/ha seedbed N should be applied to minimise leaching risk or possible damage to young seedlings, with the remainder top dressed after emergence no later than May.

Holmes (1980) summarised the results of earlier trials work both in Europe and also in Canada where N responses were more variable and often exceeded 200 kg N/ha. More recent experiments in Denmark (Augustinussen et al., 1983a; 1983b; Augustinussen, 1987) showed N

optima in the range 150-200 kg/ha and in Sweden two series of trials during the 1980s (Gudmundsson, 1989) confirmed earlier findings on N rate and timing in that country (Ohlsson, 1976). Top dressings with pig slurry have also been investigated in Denmark, these gave lower yields than slurry incorporated shortly before sowing with greater reductions in yield at later timings during the growth period (Baadsgaard, 1989). Larger application rates did not however cause further yield loss from smothering effects.

#### 4.7 Form of N Fertiliser

##### 4.7.1 Urea

Very few experiments have compared the efficiency of different forms of N fertiliser for oilseed rape. Ammonium nitrate is the major 'straight' N fertiliser used in the U.K., accounting for 61% of the 'straight' N applications to oilseed rape in 1990 (P. Leech, pers. comm.). One alternative is urea, use of which depends on availability and cost. A potential disadvantage of urea however is the risk of volatilisation loss of ammonia from the soil surface after application, following urease - mediated hydrolysis of urea to ammonium carbonate. Such losses are likely to be greater on soils with high pH and/or low cation exchange capacity, especially if the soil is warm and drying on the surface when urea is applied (Rodgers & Pruden, 1984).

Earlier work at Rothamsted on nitrification inhibitors (Rodgers et. al., 1986) had shown that yield from urea fertilised rape was on average only 90% of that from rape given the same amount of N as 'Nitro-chalk' (calcium ammonium nitrate). Urea also caused scorching when applied as a single rather than a divided application. Subsequent work there attempted to minimise the leaching loss of N and scorch damage from large amounts of urea, by applying single or multiple dressings of prilled urea and 'Nitro-chalk' in the spring (Darby & Hewitt, 1990). These comparisons gave an average efficiency of 98% for urea, based on seed yield differences. Slight increases

in seed oil content with urea application however resulted in equivalent oil yields. There were no consistent differences between timings for either form of fertiliser (Table 14).

Table 14. Mean seed yield, oil content and oil yield for the varieties Mikado and Ariana according to N fertiliser treatments, 1986-88

Rate (kg/ha) and timing of N				Seed yield		Oil Content		Oil Yield	
End-Feb	Mid-Mar	E.Apr	L.Apr	Nitro- chalk	Urea	Nitro- chalk	Urea	Nitro- chalk	Urea
				t/ha 90% DM		% (DM basis)		t/ha	
-	-	-	-	1.73		50.9		0.80	
200	-	-	-	3.26	3.28	48.4	49.1	1.43	1.46
150	50	-	-	3.34	3.18	49.0	49.4	1.48	1.42
100	100	-	-	3.28	3.16	48.9	49.3	1.45	1.41
150	-	50	-	3.22	3.16	48.6	49.2	1.42	1.41
100	-	100	-	3.16	3.17	48.6	48.8	1.39	1.40
100	50	50	-	3.22	3.31	48.7	48.6	1.42	1.46
50	50	50	50	3.33	3.27	48.3	48.6	1.46	1.44
S.E.				0.053		0.19		0.024	

Source: Darby & Hewitt (1990)

The results indicated that urea was a suitable N fertiliser for spring top dressings on winter oilseed rape. No scorching was observed with urea, however yields were lower in the first year and, in view of earlier evidence, the authors suggested that individual urea dressings should not exceed 100 kg N/ha.

Two trials in Cambridgeshire, which compared prilled urea with ammonium nitrate at a range of N rates showed that urea was as effective as ammonium nitrate for spring top dressings on winter rape (Anon, 1986b; 1987b). Experiments in Scotland in 1987 showed little or no difference in yield between ammonium nitrate and urea applied at 240 kg N/ha as top dressings in the spring (Anon, 1987c). Similar



results were obtained in a series of ADAS experiments comparing these two forms of N fertiliser on winter cereals (Lloyd, 1985), although this was in contrast to the findings from other trials work (Chaney & Paulson, 1988). Since most top dressings of N are applied between late February and the end of March, when topsoils are still moist and relatively cool with a good crop cover, the risk of ammonia volatilisation is minimal.

#### 4.7.2 Liquid N

Experiments elsewhere in Europe have examined the relative efficiencies of several different types of N fertilisers, including liquid form. Experiments in Germany (Franck & Becker, 1982) showed that calcium ammonium nitrate prills and liquid N fertiliser (as ammonium nitrate plus urea) were equally effective. Field trials in Czechoslovakia, comparing calcium ammonium nitrate and urea at each of two N rates and spring timings on traditional and single low varieties of winter rape, found no differences in yield response between the two types of N fertiliser (Voskerusa, 1979). Earlier work there on medium and heavy textured soil types had shown that urea was suitable for both seedbed application and also as a solid or liquid top dressing in the spring (Voskerusa, 1975). The requirement for fertiliser N was only moderate in these trials and the higher rates of urea (150 kg N/ha) as solid or liquid dressings caused some plant damage, more so in liquid form, compared with calcium nitrate. Foliar scorch also occurred with liquid N fertiliser in Belgian trials over the period 1967-74 where application rates of 100 or more kg N/ha were liable to cause leaf damage (Delhaye, 1980). Leaf scorch is however unlikely to affect yield unless it is severe and causes substantial defoliation.

#### 4.8 N and Seed Quality

##### 4.8.1 Oil Content and Composition

It is a well established fact that increasing the supply of N to the oilseed rape crop almost always reduces seed oil content (Fig. 4), since the resulting increased potential for protein formation

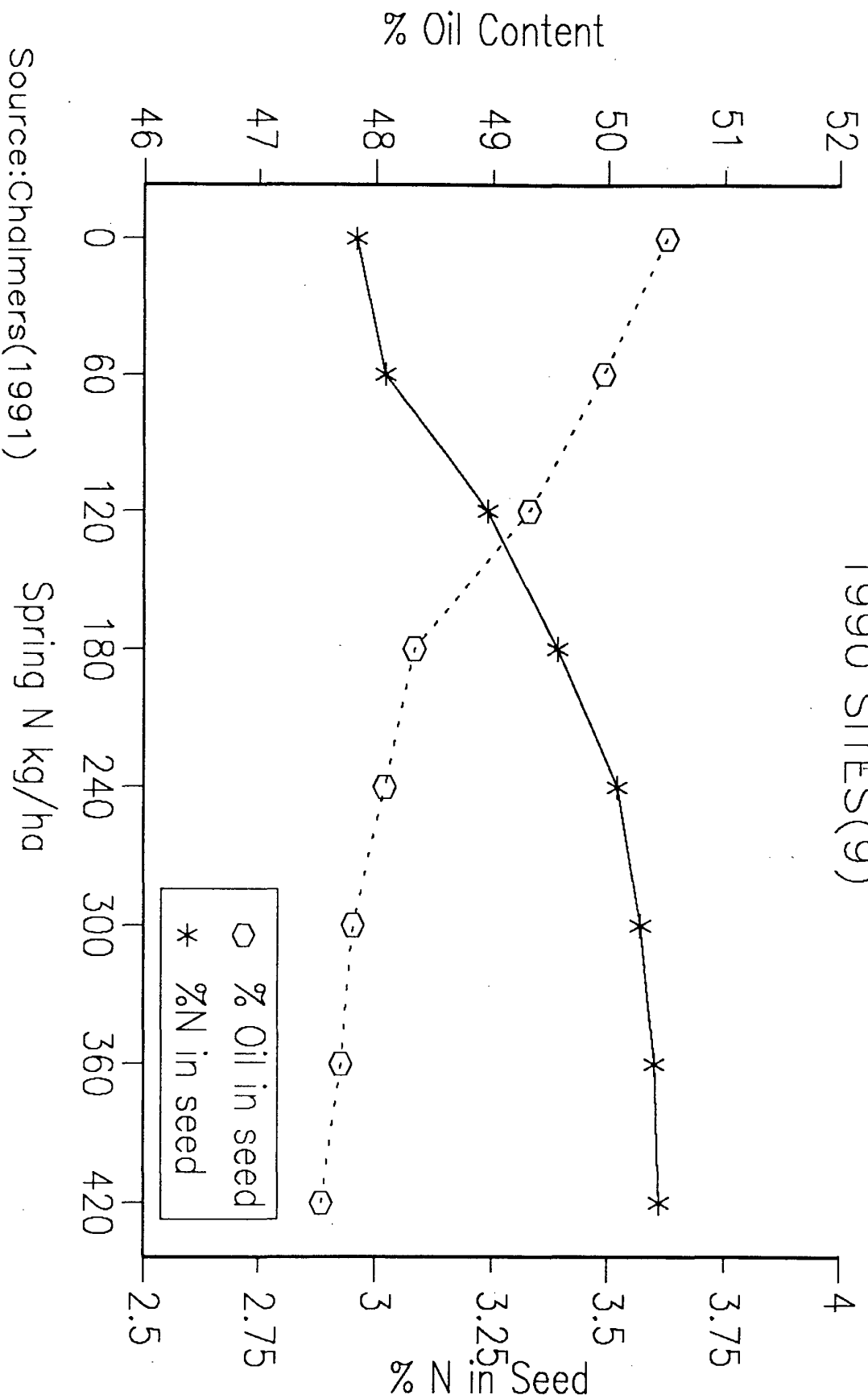
competes more strongly for photosynthates than the process of fat synthesis. Holmes (1980) summarised trials data on the magnitude of this depression in oil content, which can vary in winter oilseed rape from 0.8 to 2% of oil content per 100 kg/ha spring N applied. In U.K. trials, including the Rothamsted multi-disciplinary experiments, this depression ranged on average between 0.8 and 1.25% oil (DM basis) per 100 kg/ha N over a wide range of spring N rates (Holmes & Ainsley, 1979; Archer, 1985; Chalmers, 1991; R. Darby, pers. comm.). However these decreases are not large enough to change the economic optimum rate for seed yield. The application of seedbed N gave only minor or negligible reductions in seed oil content in U.K. trials (Holmes & Ainsley, 1978; Archer, 1985; Chalmers, 1991), similar results have been reported elsewhere (Goralski & Mercik, 1970).

Decreases in oil content with increasing N application for spring oilseed rape are smaller, typically 0.6 to 1.2% oil per 100 kg/ha N applied, with the least depression occurring under U.K. conditions (Holmes & Ainsley, 1977).

Effects of spring timing on oil content have generally been insignificant for both winter and spring-sown crops. A split application to spring rape only caused a small reduction of 0.3% compared with a single, seedbed dressing (Holmes & Ainsley, 1977).

The fatty acid composition of rapeseed oil is mainly determined by genetic factors. Nitrogen effects on the proportions of individual fatty acids in early varieties of oilseed rape were studied by Appelqvist (1968), Babrzecka et al. (1973), Kolodziej-Debowska (1973), Mazur et al. (1977), Diepenbrock (1978) and Konicka (1978a). Although the results showed that an adequate N supply can promote elongation of the fatty acid carbon chain and desaturation in such varieties, Holmes (1980) concluded that N fertiliser had only minor, if any, effect on oil composition. Very limited data for single low varieties, also indicate little effect of spring N on fatty acid composition (Holmes & Bennett, 1979). Such information is lacking for double low varieties but it is unlikely that N nutrition would have a significant effect on the fatty acid composition of these newer varieties.

Fig.4 NITROGEN FOR OILSEED RAPE-ADAS TRIALS  
1990 SITES(9)



Source:Chalmers(1991)

Spring N kg/ha

#### 4.8.2 Glucosinolate Content

The original intention within the European Community to lower the earlier limit on seed glucosinolate (GLS) content for a premium payment from 35 to 20 micromoles per gram focused attention on agronomic, as well as other factors which may influence this aspect of seed quality.

Earlier work in Europe and Canada had shown that increasing application of N usually decreased the GLS content of rapeseed, associated with a decrease in sulphur content. This was assumed to be a simple dilution effect resulting from increased dry matter production (Holmes, 1980). These decreases were however very minor in comparison with the influence of genetic improvements. Variable effects were obtained in pot experiments in Germany depending on N rate and timing (Herrmann, 1976). Subsequent pot experiments with single low varieties showed increases in GLS content with increasing application of N (Forster, 1978). However no changes in GLS contents occurred in field trials with double low varieties of spring oilseed rape or single low varieties of winter oilseed rape during 1979 to 1982 (Augustinussen et al., 1983a; Nordestgaard et al., 1984).

Recent trials on double low varieties of winter oilseed rape in England showed that GLS content increased with increasing rates of spring N at most sites, on average by about 1.5 micromoles/gram seed per 100 kg N/ha applied over the range 60 to 300 kg N/ha, but seedbed N had no effect (Chalmers, 1991). Experiments at Newcastle and Rothamsted showed larger increases in GLS content with increasing spring N of 5 to 6 micromoles/gram over the range 0 to 150 kg N/ha, with smaller effects at larger N rates except where a higher seed rate had been used (Evans et al., 1989). These results indicated that N application can increase seed GLS content provided the supply of S is adequate, and that GLS concentrations are more likely to be influenced by N uptake per plant rather than by the total amount of N applied to the crop. Where it was tested, timing of spring N did not influence GLS content. The mechanism for this N effect is uncertain, although it may be an indirect result of prolonged metabolic activity

in seed pods, as postulated for other agronomic factors which have increased GLS contents, such as disease control and irrigation (Merrien, 1989). Moisture stress also increases glucosinolate levels (Mailer & Cornish, 1987).

The minor increases in GLS content which can occur with increasing N application are, in common with most standard agronomic practices, unlikely to be detrimental to the quality of double-low cultivars. Soil and climatic factors have a more significant influence as well as the genetic effect of individual cultivars.

#### **4.8.3 Protein Quality**

Protein content of rapeseed is inversely related to oil content and is almost invariably increased by applying N in the spring, with little effect from seedbed N or timing of spring N. Earlier work, summarised by Holmes (1980), indicated approximately linear increases of 1% protein ( $\% N \times 6.25$ ) per 50 kg/ha N applied up to 350 kg/ha. More recent experiments (Chalmers, 1991) show a similar effect of spring dressings N fertiliser on seed N content (Fig. 4). Josefsson (1970) and Konicka (1978b) studied the effects of N on amino acid composition which is generally considered to be satisfactory for animal nutrition. The use of rapemeal in animal feedingstuffs is however influenced by GLS content.

#### **4.9 N and Irrigation**

Most oilseed rape is grown in the U.K. on heavier textured soils with adequate to large reserves of available water, or in areas with more favourable distribution of spring and summer rainfall so that yield loss due to moisture stress is not normally a major limiting factor in crop productivity. Drought stress is however a greater potential problem on coarser textured soils and, depending on the type of crop rotation and existing irrigation facilities, this raises the issue of the economic viability of irrigating oilseed rape in dry years. Irrigation could also become more important if the so-called 'greenhouse' effect does subsequently result in a climatic shift to

drier conditions in some areas of the U.K. Nutrient uptake by crops is affected by soil moisture status, any interactive effect between irrigation and nutrient supply is however most likely to be evident with N.

A series of experiments at Gleadthorpe EC on light land in Nottinghamshire investigated the use of irrigation on a double low variety of winter oilseed rape from 1986 to 1988 (Bailey, 1990b). In 1986 irrigation after flowering, when a period of dry weather occurred, increased yield by 0.32 t/ha. In 1987 however June rainfall was sufficient to prevent drought stress in the crop after moisture deficits had built up prior to the end of flowering. As a result, irrigation treatments before and during flowering both decreased yield, although early irrigation increased vegetative growth. Overhead irrigation applied at flowering could interfere with fertilisation and may explain the yield depression observed. This latter timing also decreased yield in 1988 and predisposed the crop to subsequent lodging, whereas irrigation after flowering increased yield on average by 0.45 t/ha. Oil content was usually unaffected except in 1988, when irrigation during flowering caused a small decrease of about 1% oil content.

These results are fairly consistent with those from French experiments on both winter and spring oilseed rape. There, drought early in the season (before mid-May) had no effect on yield but drought immediately before, during or after flowering could reduce yield. However, no interaction between irrigation and N rate was obtained by Debouzie *et al.* (1987). Pot trials in Germany with winter oilseed rape also found that irrigation before flowering was unnecessary, but irrigation between flowering and "green maturity" was beneficial on very light soils. Detailed field and pot studies have also been made in Canada (Krogman & Hobbs, 1975; Henry & MacDonald, 1978; Rood & Major, 1984), New Zealand (Davidson, 1976; Richards & Thurling, 1978; Bhan *et al.*, 1980; Bram, 1981; Stoker & Carter, 1984) and Australia (Wright *et al.*, 1988). These experiments also showed that oilseed rape is most sensitive to moisture stress during or after the flowering period and that irrigation at those

stages could give substantial yield increases. Irrigation also improved the efficiency of N fertiliser use, although optimum rate was unaffected.

As a general summary, it is likely that irrigation would only be beneficial if the soil moisture deficit (SMD) exceeds 75 mm before flowering under U.K. conditions. The Gleadthorpe results suggest that overhead irrigation should not be applied during flowering and only specialised equipment, such as centre-pivots or linear move irrigators which would not damage the crop, should be used to irrigate after flowering when the crop would be impenetrable to mobile hose-reel irrigators (Bailey, 1990b). Late irrigation will also increase the risk of Alternaria and Botrytis diseases in the wet microclimate beneath the crop canopy.

#### 4.10 Effects of nitrification inhibitors

Nitrification inhibitors delay the bacterial oxidation of ammonium-N to nitrate-N thereby slowing the build-up of nitrate in the soil which may then be subject to leaching loss. The main inhibitors available commercially are Didin (dicyandiamide) and N-Serve (Nitrpyrin). Their use can reduce N losses in both grassland and arable cropping (Rodgers & Ashworth, 1982; Rogers et al., 1985; 1987; Rodgers, 1986). A nitrification inhibitor is now included in some fertilisers in an attempt to improve N utilisation and minimise the risk of nitrate leaching losses. Few experiments have been reported however on the effect of these inhibitors on oilseed rape.

Work at Rothamsted (Rodgers et al., 1986) compared prilled urea, with or without the nitrification inhibitor dicyandiamide or the urease inhibitor hydroquinone with calcium ammonium nitrate ("Nitro-chalk") on winter oilseed rape in two seasons. Urease inhibitors retard the hydrolysis of urea and limit the associated localised rise in soil pH with its attendant problems. Each form of N was tested at 50 kg N/ha in the seedbed and was also tested in a spring application of 150 kg N/ha as a single or split top dressing. Scorching of plant leaves was severe in spring after the application of urea or urea plus

dicyandiamide but was much less when applied with hydroquinone or when the dressings were split. Volatilization losses from 'Nitro-chalk' were negligible and less than 2% from urea. 'Nitro-chalk' was the more effective form of N for yield in this set of experiments probably because leaf scorching from urea affected yield. The application of dicyandiamide did not improve the efficacy of urea although it did inhibit the nitrification of urea-derived ammonium. Oil and seed yield from the urea plus hydroquinone treatment were consistently larger than from urea alone especially when single dressings of N were applied. Hydroquinone reduced ammonium losses from the soil, however such losses were small and did not exceed 3% at maximum. Neither inhibitors affected the soil pH changes caused by urea application.

Other work at Rothamsted by Rodgers and Pruden (1984) tested hydroquinone with  $^{15}\text{N}$ -labelled urea, applied as a March top dressing at 150 kg N/ha to winter oilseed rape. Ammonia volatilization losses were estimated by a  $^{15}\text{N}$  balance procedure by determining the amount of  $^{15}\text{N}$  taken up by the crop or remaining in the soil to 70 cm depth eighteen days after urea application. A 100% recovery of urea-N was obtained whether or not hydroquinone had been applied, indicating no volatilization loss of ammonia from the high pH soil probably because it was too cold, too wet and had a high cation exchange capacity. These and other results indicate that top dressings of urea at the start of spring growth do not require a urease inhibitor for full N efficiency.

Experiments in Russia and Czechoslovakia, with fodder rape as a test crop, showed positive effects on yield and quality from using dicyandiamide (Sokolov *et al.*, 1986) or nitrapyrin (Savenkov, 1979; Lavrova *et al.*, 1981). In Canadian trials, testing different rates of N applied in the spring or autumn as ammonium nitrate, solid urea or liquid N with or without nitrapyrin, it was concluded that nitrapyrin should not be used as a nitrification inhibitor on oilseed rape, mainly because it lowered seed oil content (Bailey, 1990a). In Germany the use of guanylurea, calcium cyanamide and dicyandiamide were found to have strong inhibitory effects on the germination and



apothecia formation of sclerotia from Sclerotinia sclerotiorum (Fink, 1989). Similarly Mitchell and Wheeler (1990) found in pot trials that fewer apothecia were produced where N fertiliser was added as ammonium nitrate, compared with no addition of N fertiliser.

#### 4.11 N and Growth Regulators

A tall, dense canopy in oilseed rape could potentially restrict yield by shading effects, as well as making field operations more difficult and increasing the risk of lodging with its attendant problems. The use of plant growth regulators (PGRs) to reduce the height of tall varieties by manipulating crop structure, thereby maintaining erectness and increasing light interception at critical stages, has been seen as a potential benefit for yield and management.

A number of experiments in the U.K. have examined the potential benefits from applying PGRs. Experiments during 1981 to 1983, with PGRs which are widely used on cereals, showed few yield responses from autumn or spring application at early stem extension on winter oilseed rape, although some treatments reduced crop height (Bowerman, 1984). Daniels et al. (1982) had tested a similar range of PGRs but in combination with 0, 100 or 200 kg/ha N. Scottish trials in 1989 and 1990 gave small and economic yield responses to spring application of Cycocel, these were not however statistically significant and no positive interaction occurred with N (Walker, 1989; 1990b).

Application of the growth retardants triapenthenol and BASIII..W altered crop morphology but gave inconsistent effects on yields in field and associated pot experiments at Long Ashton (Child & Evans, 1989). Field trials at Morley Research Centre from 1987 to 1989 gave consistent yield increases with triapenthenol averaging 13 and 7% in Cobra and Libravo respectively, but variable results for Ariana (Palmer & Stevens, 1990). Triapenthenol consistently shortened stem height, but the variable effect on yield may have been related to critical growth stages at the time of application. Treatment with Triapenthenol, but not Ethephon, increased yield by 4 to 17% in the

multi-disciplinary and allied experiments at Rothamsted (R. Darby, pers. comm).

Experiments in Poland (Osinska, 1976), Czechoslovakia (Vasak, 1983), Germany (Marquard & Alter, 1987; Gendy & Marquard, 1989) and elsewhere in Europe have shown significant effects of PGRs on crop height, structure and lodging propensity, but little or no benefit to yield. Although few experiments have tested N x PGR interactions in detail, the results from U.K. trials also indicate little potential for the use of PGRs on oilseed rape, particularly if current developments in crop breeding produce shorter varieties with a more determinate pod canopy.

#### 4.12 N Fertiliser Residues after Winter Oilseed Rape

Mineral N residues in the soil (0-90 cm depth) after cereal cropping in a continuous arable rotation can vary from 20 to 146 kg N/ha, according to soil type, when measured in October (Darby et al., 1986; Widdowson et al., 1987; McEwen et al., 1990). These authors also showed that larger N residues occur after break crops or recent ploughing out of long term grassland where residues sometimes exceed 300 kg N/ha.

<sup>15</sup>N labelled ammonium nitrate was used in the 1984-85 multi-disciplinary experiment at Rothamsted to follow the fate of N fertiliser applied in the spring to winter oilseed rape. Although yield response to applied N was small, the crop recovered 66% of the labelled N fertiliser, half of which was in the seed and a further 16% remained in the topsoil (0-23 cm). The remaining 18% of the N was not accounted for, due to leaching, denitrification or volatilisation losses. Additional spring timing treatments with labelled fertiliser showed similar N recoveries with single and split dressings ranging from 66 to 71% when crop N uptake was measured after flowering.

Winter wheat was then grown as the following crop with different amounts of residual labelled N, supplied from either soil + rape stubble (63 kg N/ha) or rape straw (50 kg N/ha). Labelled wheat straw, providing 23 kg N/ha, was also included as a third comparison. The wheat crop took up 22%, 11% and 6% respectively of the labelled N from these three sources, leaving 42%, 41% and 35% in the soil. The results clearly showed that the labelled N contained in the rape stubble and soil residue was utilised much more effectively by the wheat crop and that unaccounted losses of labelled N from rape or wheat straw alone were greater, ranging from 48% to 59% (P.R. Poulton, pers. comm.). In overall terms, only a relatively small proportion of the residual N after oilseed rape was recovered by the following cereal crop, with some longer term retention of the remaining residue in soil organic matter after other, unaccounted N losses had occurred from the plant-soil system. Longer term immobilisation of N fertiliser residues and subsequent release by mineralisation processes in the soil are discussed by Johnson & Jenkinson (1989).

Current work at Rothamsted aims to quantify the leaching of fertiliser-derived nitrate from several soil types, cropped with a range of arable crops including winter oilseed rape (A.J. MacDonald, pers. comm.). At normal yield levels oilseed rape, receiving 235 kg N/ha as labelled fertiliser, recovered between 48% and 51% of the labelled N, with 24% to 29% contained in the seed. Of the fertiliser derived N, 22% to 26% was left in the soil after harvest, similar to the proportion found after winter wheat, and on average 84% of the labelled residue was in organic, rather than mineral, N form. Only 3-4% of the fertiliser N applied to oilseed rape remained in the soil at harvest as inorganic N (equivalent values for winter wheat were 2-3%). The return of organic N derived from stubble and roots was estimated from the ratio of labelled and unlabelled N in straw, rape crops normally left 29 kg N/ha more organic N than did wheat.

The utilisation of these crop residues was assessed in the following season by growing winter wheat and spring barley. The amount of fertiliser-derived N found in the soil after rape ranged from 65 to

89 kg N/ha. However the proportion of this labelled N recovered in the following wheat and barley crops at harvest was generally small, ranging from 5% to 10% of the original soil residue after rape (equivalent to 3% to 5% of the cereal crop uptake).

Futher experiments in the following season with two N rates showed a wider range of N recovery by rape, ranging between soil types from 34% and 56% of the labelled N again with approximately half of this N in the seed. The proportion of labelled N remaining in the soil varied from 28% to 39%, approximately twice the proportion retained after wheat except in a clay soil where wheat and rape left similar amounts. Only 5% of the residual labelled N was present in readily available inorganic form after harvest (A.J. Macdonald, pers. comm.). Data on residual N effects in the following cereal crops have not been completed yet.

In conclusion, these preliminary results, limited to a few sites and seasons, showed that recovery of labelled N fertiliser by oilseed rape varied considerably with soil and season and ranged from 34% to 70% with about half of this N contained in the seed. Where poor crop recovery of labelled N occurred the amount of labelled fertiliser N remaining in the soil was appreciable, up to 39% of that applied, otherwise the proportion left varied between 22% and 33%. Of these soil N residues after oilseed rape, 84% to 95% were organically bound and not immediately available to the following crop. Where residual N was derived from both soil, roots and stubble, a larger proportion was utilised in the following crop than where derived from straw alone. Estimates of the return of organic N from stubble showed that rape returned approximately 30 kg/ha more N than wheat. Of the 65 to 90 kg/ha of fertiliser derived N found in the soil after rape, only 5-10% was found in the succeeding crop which represented only 3-5% of the crop uptake. No other work appears to be published on the origin and fate of <sup>15</sup>N labelled residual N from oilseed rape.

ADAS measurements of soil N supply (soil mineral N (0-90 cm depth) + plant N uptake, in kg/ha) over a period of many years at both experimental sites and fields monitored annually on a national basis,

have shown appreciable N residues after oilseed rape (B. Chambers, pers. comm.). This residual N fertility translates into a reduction for the next crop of between 40-80 kg N/ha compared with wheat following cereals. The lower end of this reduction relates to light soils and the higher end to clays. In future years however the amount of N residue will be less, because of the lower optimum rates of N fertiliser for oilseed rape under the new price regime. The magnitude of this N residue, and the associated potential saving in N fertiliser use for the following crop, is currently under review.

#### 4.13 Conclusions

1. Nitrogen has a major effect on yield and, although 90% of the yield response is obtained with approximately 60% of the optimum N rate, it is still economic to apply moderately large amounts of N fertiliser.
2. Greater use of N increases vegetative growth and subsequent branching of the oilseed rape plant. Nitrogen application does not appear to influence the sequence of flower development but delays and prolongs the flowering period. Increases in yield with increasing N rate are mainly associated with greater numbers of pods as a result of more biomass production during the growth period before flowering. The effects of N on seed number and seed weight are less consistent and generally slight. Plant population, as another component of yield, is very rarely affected by N use.
3. Yield responses which occur in some situations for winter oilseed rape with the use of autumn N fertiliser are usually small but can be economic. In some experiments however it is not clear whether the apparent responses are a unique, or total N, effect of N application in the autumn as well as in the spring. Possible factors which may contribute to a unique yield response with autumn N are poorly understood at present, although recent ADAS experiments have shown that the method of preceding straw

disposal affects crop requirement for autumn N. Under U.K. conditions 50 kg N/ha, either applied to the seedbed or top dressed by the two leaf stage and no later than early October, has until recently been recommended in most situations for soils with low N fertility. In England and Wales, 30 kg/ha autumn N is now recommended as a result of the recent reduction in rapeseed prices.

4. Crop requirement for spring N fertiliser depends on the N status of the soil and yield potential. Recommended rates for spring application previously ranged from 200 to 280 kg N/ha for winter oilseed rape, according to site factors, and 125-150 kg N/ha for spring-sown oilseed rape in normal arable rotations. These rates have been reduced by up to 50 and, provisionally, 30 kg N/ha for winter and spring-sown crops respectively under the new EEC price structure. Measurement of soil N supply does not improve the accuracy of predicting N requirement, unless the soil is more fertile than usual. The appreciable residue of N left after oilseed rape means, however, that less N fertiliser is needed for the following winter wheat crop.
5. There is normally little or no advantage for winter oilseed rape from a split application of spring N fertiliser compared with a single top dressing during late February to early March at the start of spring growth. For management purposes however split dressings are often preferable, with up to half applied when spring growth starts and the remainder by the end of March to mid April, prior to stem elongation. Split dressings should also be used on soils where there is a high risk of leaching in early spring. Very early or late split dressings are not generally advantageous economically or environmentally.

Split dressings, rather than a single application to the seedbed, should be used for spring crops which are either sown early or where there is a high risk of spring leaching.

6. Increasing rates of spring N fertiliser decrease seed oil content, the effects are not however large enough to change the optimum N rate for yield and N has little effect on the fatty acid composition of the oil. Recent experiments have shown small increases in seed glucosinolate content with increasing rates of spring N fertiliser, the mechanism for this effect is however uncertain. Autumn N use has a negligible effect on seed quality.
7. Urea has a similar efficiency to ammonium nitrate for top dressing winter oilseed rape in the spring, as the risk of ammonia losses by volatilisation is minimal at that stage. The use of nitrification or urease inhibitors with spring dressings of urea have not shown any advantage at normal times of application. Irrigation can increase yield if large moisture deficits build up in the soil before flowering. Specialised irrigation equipment is however needed to irrigate the crop after flowering without causing crop damage, and late irrigation gives an increased risk of disease infection. Experiments with PGRs have not consistently given any increase in yield or positive interaction with N rate.

## 5. PHOSPHORUS, POTASSIUM AND MAGNESIUM

### 5.1 Phosphorus

#### 5.1.1 Role in Plant Nutrition

Oilseed rape, in common with other crops, takes up less phosphorus (P) than either N or potassium (K). Phosphorus has a wide and fundamental range of functions in plants (Chapman, 1973). Organic P compounds are involved in energy transfer reactions as adenosine triphosphate (ATP) in the process of respiration. Phosphorus is also a constituent of nucleic acids and nucleoproteins, responsible for transmitting hereditary characteristics. It is a relatively mobile nutrient within the plant, readily translocated to younger, actively growing tissues as the crop develops. Deficiency symptoms are rare and vary with severity, but typically show as dark bluish-green leaves, sometimes with purple or reddish colouration. Where deficiency is slight, the crop tends to recover after some growth restriction at the rosette stage. As the deficiency becomes more severe, the crop becomes stunted with spindly growth and restricted branching, flowering is also reduced or in extreme cases prevented.

The chemistry of P in soil greatly affects the availability of this nutrient to plants (Brady, 1974).

#### 5.1.2 P Uptake and Removal

Oilseed rape is well able to extract P from soil, probably because of its fine roots and abundant, long root hairs (Brewster *et al.*, 1976) which can explore a large volume of soil. Also root exudation of organic acids, which is the likely cause of localised acidification in the rhizosphere around the roots where the P supply is limited (Hoffland *et al.*, 1989), may render native soil P more soluble and explain the poor yield response of oilseed rape to P fertiliser. As for other crops, P uptake by oilseed rape is affected by temperature (Cumbus & Nye, 1985). The root:top fresh weight ratio in rape seedlings has been observed to decrease with increasing P supply



(Schjorring & Jensen, 1984) indicating less need for an extensive root system to provide an adequate uptake of P.

Little information on P uptake is available from U.K. work. Data from other countries, mostly France, has shown that maximum uptake which normally occurs at crop maturity, is typically 70-125 kg/ha  $P_2O_5$  for winter oilseed rape but as little as 35-65 kg/ha  $P_2O_5$  for Canadian crops of summer rape (Holmes, 1980). Barraclough (1989) recorded a maximum uptake of 98 kg/ha  $P_2O_5$  at the end of June for a high yielding crop at Rothamsted, uptake of P as well as other nutrients declined between then and final harvest, possibly because not all of the leaf litter was collected.

Uptake by winter oilseed rape in the autumn can vary between 2 and 22 kg/ha  $P_2O_5$  according to the amount of growth. Subsequently, total P uptake follows an s-shaped pattern with the most rapid phase during May and June. Most of the P is translocated to the pods and seed before the leaves are shed. In Canadian field experiments, a larger proportion of P uptake in spring rape occurred during early growth stages (Strong & Soper, 1974). Phosphate removal in harvested seed of both winter and spring rape grown in the England is around 15-16 kg  $P_2O_5$ /tonne (Holmes & Ainsley, 1977 & 1978; Archer, 1985), average offtakes of 12-14 kg  $P_2O_5$ /tonne are used in Scotland (Dyson & Sinclair, 1990).

#### 5.1.3 Effect of P Fertiliser on Seed Yield and Quality

The application of P has seldom had much effect on crop growth or yield in U.K. conditions as the majority of soils have adequate reserves of soil P (Church & Skinner, 1986). Consequently effects on yield components have not been examined in detail. Pot experiments in Poland indicated that only 3-6% of applied phosphate fertiliser was taken up by spring rape (Staud, 1985), recoveries of about 5-10% have been recorded for other crops (Archer, 1985).

Holmes & Ainsley (1978) found small average responses of 0.04 (1.4%) and 0.07 (2.5%) t/ha to 45 and 90 kg  $P_2O_5$ /ha applied as

superphosphate, for thirty three sites in England and Scotland. Phosphate fertiliser only increased yields significantly at four sites, which were on soils with low or moderate levels of available soil P. In another series of experiments at twenty two sites in England (Archer, 1985), the overall yield response to phosphate was just sufficient to cover the cost of the fertiliser (Table 15). Worthwhile yield responses were only obtained at low soil P status, Index 0-1 (MAFF, 1986).

Table 15. Winter oilseed rape response to phosphate, ADAS experiments

Soil Index	Number of sites	Yield response (t/ha)	
		25 kg P <sub>2</sub> O <sub>5</sub> /ha	50 kg P <sub>2</sub> O <sub>5</sub> /ha
0-1	8	+ 0.13	+ 0.19
2	7	+ 0.12	+ 0.10
3+	7	- 0.12	- 0.07

Source: Archer (1985)

The negative effects at Index 3+ were small and variable, no sites showed a worthwhile benefit to rates above 50 kg P<sub>2</sub>O<sub>5</sub>/ha.

Yield responses of 2-17% from 60 kg P<sub>2</sub>O<sub>5</sub>/ha applied to spring oilseed rape were only obtained on soils with very low to low P status in U.K. trials across twenty six sites (Holmes & Ainsley, 1977). These results indicated a slightly greater responsiveness to phosphate fertiliser applied to soils of low P status, compared with winter oilseed rape (Table 16).

Table 16. Effect of P fertiliser and soil P status on seed yield (t/ha) of spring oilseed rape - 1973-75, 26 sites

Soil P Index*	Number of sites	$\frac{P_0}{P_5}$ Rate, kg/ha	60
1	6	1.45	1.69
2	7	1.63	1.66
3	8	1.78	1.79
4	4	1.60	1.60
5	1	3.34	3.25

\* Resin extract method

Source: Holmes & Ainsley (1977)

Experiments in Poland (Dembinski *et al.*, 1969), Switzerland (Gisiger & Bonjour, 1967) Norway (Stabbetorp, 1973) and Canada (Soper, 1971; Ukrainetz *et al.*, 1975) also indicated that yield responses to applied P fertiliser were related to soil P status, although there was conflicting evidence on the optimum amounts of P fertiliser required. Oilseed rape was less responsive than cereals to P or K fertiliser in Dutch experiments on clay soils, also excessive application of P caused some leaf scorch and only moderate rates of application were recommended (Prummel, 1978). Subsequent work in Canada, where placement of at least some of the P fertiliser with or near the seed has been recommended, tested the effects of broadcasting (Sheppard & Bates, 1980) or deep banding (Nuttall & Button, 1990) of P fertiliser in addition to fertiliser placement close to the seed. With broadcasting only, a larger amount of P fertiliser was required to give the same yield increase as a banded application on responsive soils with low soil P status. Deep banding of P fertiliser generally gave similar yields to placement with the seed but was less effective at lower application rates under dry conditions. Fertiliser placement studies were also made on other soil types (Bailey & Grant, 1990). Yield responses to P fertilisers have also been studied in Australia (Osborne & Batten, 1978; Dann & Edwards, 1979; Strong & Barry, 1980; Lewis *et al.*, 1987) and generally correlated well with soil P status.

Effects of P fertiliser on oil content, as summarised by Holmes (1980), are usually very slight and do not influence fertiliser requirements. A higher rate of P fertiliser is needed in deficient situations to ensure satisfactory oil content as well as yield. Similarly, any effect on the fatty acid composition of the oil, protein and glucosinolate contents of the seed are also very minor.

## 5.2 Potassium

### 5.2.1 Role in Plant Nutrition

The main role of K in plants is to regulate the cell water content and activate a wide range of enzyme systems (Mengel & Kirkby, 1987). Maintenance of cell turgor and maximum rates of cell expansion depend on cell K concentrations. Other physiological functions controlled by K include stomatal movement of the leaves, chloroplast formation and hence photosynthesis and transport of photosynthates within the plant (Morard, 1974). A high concentration of K ions is needed in young actively metabolising tissue to activate enzyme systems effectively. In contrast to other essential elements, K is present in unbound form in the cytoplasm, rather than as component organic molecules in cell tissues. Consequently K is readily released once plant tissues dies.

Deficiency symptoms are similar to those of other dicotyledonous plants, with leaf darkening which develops into marginal or interveinal chlorosis often followed by necrotic patches. Older to middle leaves are affected, depending on growth stage when deficiency occurs. Potassium, as well as P deficiency is rare in the U.K. and most likely to occur on sandy soils of low K status or where seedbed consolidation is very poor. The soil chemistry of K is well documented (Wild, 1988) and has been summarised in the context of cereal requirements for both this nutrient and P (Arnold & Shepherd, 1990). Kuchenbuch & Jungk (1984) studied K availability and depletion in the vicinity of roots of rape seedlings.

### 5.2.2 K Uptake and Removal

Most information on K uptake, as for N and P, has been obtained in continental experiments. Winter oilseed rape takes up large amounts of K and maximum uptake, between 150 and 300 kg  $K_2O$ /ha, is mainly related to the extent of dry matter production (Holmes, 1980). Uptake in the autumn varies between 15 and 55 kg  $K_2O$ /ha, or even more in very forward crops. Rapid uptake during the main period of spring growth results in maximum crop content around the end of flowering, with a subsequent decrease by harvest. Calculation of nutrient fluxes into the root system of a high yielding crop indicated that transport of K, and other major nutrients in the soil by diffusive supply did not limit uptake (Barracough, 1989).

Offtake of potash in harvested seed of both winter and spring oilseed rape in England is about 11 kg  $K_2O$ /tonne (Holmes & Ainsley, 1977 & 1978; Archer, 1985), whereas Scottish data suggests 7 kg  $K_2O$ /tonne (Dyson & Sinclair, 1990). Similar levels of offtake have been found elsewhere in western Europe, confirming that K removal in harvested seed is relatively low compared with total uptake.

### 5.2.3 Effect of K Fertiliser on Seed Yield and Quality

Several series of experiments in the U.K. during the 1970s tested responses to freshly applied K fertiliser. Thirty-four trials on winter oilseed rape (Holmes & Ainsley, 1978) showed little response to K as few sites were on soils of low K status (Table 17).

Table 17. Effect of K fertiliser on seed yield, seed oil and K content of winter oilseed rape 1973-1975, 34 sites

K <sub>2</sub> O Rate	Seed Yield	Oil Content	K Content
kg/ha	t/ha (90% DM)	% (DM basis)	% (DM basis)
0	2.89	41.0	0.78
45	2.86	40.9	0.78
90	2.93	40.8	0.79

Source: Holmes & Ainsley (1978)

A separate series of trials at twenty-two sites (Archer, 1985) gave no overall yield response in winter rape to K and no individual site responses that could be predicted from soil analysis or soil type, although nine sites were on soils with a moderately low (Index 1) K status (Table 18).

Table 18. Winter oilseed rape response to K fertiliser, 22 ADAS sites

Soil Index	Number of sites	Yield response (t/ha)	
		25 kg K <sub>2</sub> O/ha	50 kg K <sub>2</sub> O/ha
1	9	- 0.06	+ 0.02
2+	13	- 0.05	- 0.01

Source: Archer (1985)

A series of trials on fertiliser requirements for spring oilseed rape also gave little response to K fertiliser, with a mean yield response of 0.04/ha which was not related to soil K status (Holmes & Ainsley,

1977). Earlier trials work at Sutton Bonnington showed some response in winter and spring rape to large potash dressings (180 kg  $K_2O$ /ha) where input of N fertiliser was substantial (Scott et al., 1973a).

Applications of 80-120 kg  $K_2O$ /ha had been advocated in Holland for soils of normal K status (Boer, 1975). However Dutch work on clay soils found subsequently that oilseed rape was less responsive to K (and P) than cereals and only moderate fertiliser rates were recommended (Prummel, 1978). Experiments in Norway on spring rape and spring turnip rape gave small and unpredictable effects of K fertiliser, even on sandy soils and soils of low K status (Stabbetorp, 1973). A long term German trial on rate and form of K application showed yield responses in a range of crops including oilseed rape (Amberger & Gutser, 1976), which may have been related to K-depletion in some treatments. Similarly, in another long term trial in France on a sandy textured soil of low initial K status, K depletion caused subsequent yield responses to freshly applied K fertiliser, especially at higher N rates (Anon, 1971).

A three year trial on broadcasting and placement of fertiliser for Canadian spring rape showed very little yield response to K on a site with moderate soil K status (Sheppard & Bates, 1980). Earlier Canadian trials generally showed a lack of response except on soils with low K availability, where K application doubled yield (Soper, 1971). Trials in China also found that responses were related to soil K status (Chen & Zhou, 1982) and, where they occurred were mainly caused by increases in seed number per pod. Other work investigated the interactive effects of K and boron and concluded that the optimum K:B ratio in rape was 1000 (Li et al., 1989).

Both the role of K in the nutrition of oilseed rape, and crop response to K fertiliser, have been reviewed by Bailey & Soper (1985). The effects of K on crop growth and yield components of oilseed rape, are not well documented, since few experiments have shown yield responses. Studies on other crops have shown that inadequate K nutrition can cause stem weakness and increased susceptibility of plants to disease infection. Such effects might be

expected, but have not been verified for a crop of oilseed rape deficient in K.

Danish experiments on both winter (Nordestgaard et al., 1984) and spring (Augustinussen et al., 1983a) crops did not show any effect of K application on seed yield or quality. In winter oilseed rape, seed weight, oil and crude protein content were unaffected by increasing K rate, changes in fatty acid and amino acid composition were only slight and there was no observable effect on glucosinolate content. Similarly, K application had only minor effects on the fatty acid content of spring rapeseed oil. These results agree with other limited data (Appelqvist, 1968; Holmes & Ainsley, 1977 & 1978; Wetter et al., 1970) which indicate that the effects of K fertiliser on seed quality is negligible in terms of oil content and fatty acid composition, protein and glucosinolate contents.

### 5.3 Fertiliser strategy for P and K

Canadian experiments have shown that placement of P fertiliser close to the seed increases the yield of oilseed rape on soils of low P status, compared with broadcasting and seedbed incorporation of the fertiliser (Ukrainetz et al., 1975). Fertiliser placement makes the nutrient more readily accessible during the early stages of growth, particularly with water soluble P fertiliser where P immobilisation occurs subsequently. Most arable soils in the U.K. however have an adequate P and K status (Church & Skinner, 1986) so that yield responses to freshly applied fertiliser rarely occur. Other reasons for broadcasting, rather than placement, of P and K fertiliser under U.K. conditions are:

- the risk of delaying or inhibiting seed germination with fertiliser placement in dry seedbed conditions
- slower drilling with fertiliser placement
- the longer growing season which means that the need for rapid growth to establish an extensive root system is less critical.



Crop requirement for P and K, for both rate and timing, should be based on soil nutrient status, as determined by regular soil analysis every four to five years. Fertiliser recommendations published by ADAS (MAFF, 1988) and The Scottish Agricultural College (Dyson & Sinclair, 1990) take account of soil P and K status and average nutrient offtakes in the harvested crop. The Scottish recommendations also allow for situations where the crop haulm is removed for livestock bedding.

Increased rates of fertiliser are only required where the soil nutrient status is low or deficient, in order to increase yield response as well as helping to raise soil reserves in the longer term. The fertiliser should be incorporated into the seedbed, not combine drilled for reasons outlined previously. Where soil P and K reserves are satisfactory, P and K rates aim to balance crop offtake of these nutrients and can be applied on a rotational basis except for sandy soils where K should be applied annually (MAFF, 1985). In this situation timing of P and K application is very flexible, whether as an annual or bulk dressing for the rotation, and can be broadcast at any convenient stage during the year from the preceding stubble through to a top dressing on the growing crop. This also gives a range of options for choice of fertiliser types. Where soil P and K reserves are large, fertiliser application can be reduced or omitted for a number of years, depending on economic factors and longer term farm policy on the maintenance of soil nutrient levels.

Long term experiments in Poland, comparing annual and bulk dressings of P and K every two to four years, showed similar results for both methods of fertiliser application for a range of crops including oilseed rape, except where soil P and K reserves were low (Boguszewski et al., 1972).

## 5.4 Magnesium

### 5.4.1 Role in Plant Nutrition

Magnesium (Mg) is an essential component of chlorophyll and is involved in a number of enzyme driven plant physiological processes including phosphorylation, assimilation of carbon dioxide and protein synthesis. The Mg requirements of oilseed rape are largely met by the soil although rainfall inputs can be as high as 10 kg/ha/yr near to the coast. Only a small proportion of the total soil content of Mg is available for plant uptake, availability of supply being dictated by the amount of exchangeable Mg held on soil particles. There is very little release of Mg from soil organic matter.

A shortage of Mg is therefore commonly found on sandy soils with a low cation exchange capacity, especially where the latter is dominated by other cations (i.e. very acid or alkaline soils) and Mg is subject to leaching loss. On heavier soils, weathering of soil minerals is sufficient to maintain a satisfactory pool of exchangeable Mg and solution concentrations are relatively high.

Magnesium deficiency occurs less frequently in oilseed rape than in either other brassica crops (e.g. cabbage, kale), sugar beet or potatoes where these crops are grown on soils of low Mg content. However symptoms of Mg deficiency do occur in oilseed rape on soils with a wide range of Mg contents in response to stress, either induced by drought and/or poor soil structural conditions. Symptoms always occur on the older leaves and appear as coarse, chlorotic spotting between the leaf veins. As chlorosis increases, leaves develop an orange, reddish or purple colouration. The Mg content of deficient leaves is typically less than 0.1% in the dry matter, compared with 0.15-0.20% for healthy leaves from plants which are well supplied with this nutrient. Symptoms are often transient on soils of adequate Mg status and usually coincide with periods of rapid growth as Mg is transported from older leaves to younger expanding leaves and inflorescences. Under these conditions Mg

fertilisation via foliar sprays is unlikely to be worthwhile (Archer, 1985). Deficiency symptoms have been reported to occur in autumn and can be confused with those of sulphur and manganese.

#### 5.4.2 Mg Uptake and Removal

In common with other major nutrients, uptake of Mg reaches a maximum towards the end of flowering in June although the amounts taken up at this time can vary between individual crops. For example Mg uptake figures for European crops reviewed by Holmes (1980) range from 11-33 kg/ha and high yielding crops in the U.K. have required from as little as 16 kg/ha (Barracough, 1989) to as much as 40 kg/ha (Almond *et al.*, 1986). Whole plant Mg concentrations can show similar variation (0.1 to 0.4% in the dry matter) and tend to decrease as the season progresses.

This variation is undoubtedly a reflection of both the ability of different soils to supply Mg and the large influence that plant rooting density and seasonal weather patterns exert on Mg uptake by the plant. The uptake of Mg at the root surface is also highly dependent on concentrations of other cations (calcium, potassium and ammonium) in the soil solution and when these are in plentiful supply, especially K, the uptake of Mg is poor (Mengel & Kirkby, 1987).

Magnesium is very mobile within the plant and, during reproductive stages of growth, Mg moves readily within leaves and to the inflorescences and seed (Holmes, 1980). At harvest, Mg concentrations can be as large as 0.35% although the offtake of Mg in the seed is typically 7-8 kg/ha for an average 3 tonne/ha crop (Archer, 1985; Merrien, 1990). Magnesium concentrations of straw have been shown to increase with increasing N rate although Askew (1982) found a range of values from 0.12 to 0.19% Mg in the dry matter for three single low varieties which all received 200 kg N/ha in 1977.

#### 5.4.3 Effect of Mg Fertiliser on Seed Yield and Quality

Yield responses to applied Mg have been obtained in winter oilseed rape in Poland on acid soils of low Mg content (Jablonski & Horodyski, 1981) but there is no U.K. or European evidence to indicate that oilseed rape responds to Mg fertilisation. For example, in experiments carried out by ADAS between 1985 and 1988 there was no significant yield increase from 100 kg Mg/ha (applied to the seedbed) at 2 sites with soil Mg contents as low as 17 and 20 mg/l, Index 0 (Withers, 1988). These results indicate that oilseed rape has a relatively small demand for Mg and it has already been shown that high yields can be obtained with a relatively low uptake of Mg (Barracough, 1989). Foliar applications of magnesium sulphate (applied as Bittersalz) have given worthwhile yield increases in commercial trials in Germany (Orlavius, pers. comm.) but this has been attributed to an effect of the sulphur content rather than the magnesium component of this fertiliser.

Severe Mg deficiency is possible where prolonged stress conditions coincide with a low Mg content in the soil and, although very seldom seen, are conditions under which a yield penalty can be expected. Soil Mg levels below 25 mg/l have been shown to give rise to severe deficiency in more susceptible crops (MAFF, 1968) and advice to farmers is to ensure soil Mg contents do not fall below this level when growing oilseed rape. Magnesium fertiliser can be applied to the soil either as magnesium limestone or as magnesium sulphate (Kieserite) to correct a soil deficiency of Mg. Magnesium limestone is not recommended where soil pHs are already adequate for plant growth at pH 6.5 or more. Currently recommended inputs of K fertiliser to satisfy the maintenance requirements of oilseed rape (40 kg/ha) are not sufficient to significantly antagonise the uptake of Mg on most soils.

#### 5.5 Conclusions

1. Deficiencies of either P or K in oilseed rape are rare, as most arable soils have adequate reserves of these nutrients. Oilseed rape takes up appreciably more K than P during the growing

season, however offtakes of both nutrients in harvested seed are moderate and slightly greater for P than K.

2. Yield responses to fresh dressings of P or K fertiliser are only likely to occur where the soil status is very poor. Applications of P and K usually have no significant effect on seed quality.
3. Fertiliser requirements depend on soil nutrient status and yield level, in most cases only maintenance P and K dressings are needed to balance crop offtakes. In this situation, timing of fertiliser application is flexible, whether as annual or bulk dressings for the rotation.
4. Oilseed rape is not very susceptible to Mg deficiency, which is most likely to occur on sandy soils with low Mg status. However this deficiency can be induced on a wide range of soils under conditions of crop stress caused by poor soil structure, restricted rooting and/or drought.
5. Symptoms of Mg deficiency are often transient, unless soil reserves of Mg are very low, and foliar application of Mg fertiliser are unlikely to increase yield.
6. Experiments in the U.K. have not shown any yield response in oilseed rape to seedbed applications of Mg fertiliser but soil reserves of Mg should be maintained at a satisfactory level for arable rotations to avoid any risk of Mg deficiency limiting yield.

## 6. SULPHUR

### 6.1 Introduction

Sulphur (S) has been referred to as the fourth major nutrient and for oilseed rape this title seems well justified. In common with other members of the Cruciferae family, oilseed rape has a large demand for S and there has been considerable interest in recent years in the extent to which the crop requires supplementation with S fertiliser. The idea that S may be limiting crop yields in the U.K. gathered momentum with the launch in the early 1980s of a commercial product based on micronised elemental S and designed for foliar application. This product was called Thiovit and claims over its effectiveness centred around the question of whether S was acting as a fungicide, nutrient or both. Although it is well known that S can act as a broad spectrum fungicide (McGrath & Johnson, 1986) extensive trial work has since demonstrated the importance of S as a nutrient. The influence of S supply on glucosinolate synthesis has also received much attention in recent years because of the need to keep the glucosinolate content of rapeseed to a minimum to improve the feed quality of the rapemeal after the oil has been extracted from the seed.

### 6.2 Crop Requirement

Sulphur is an essential component of the amino acids cysteine and methionine that are required for the synthesis of proteins, and therefore of all enzymes, in particular those such as ribulose biphosphate dehydrogenase which are involved in photosynthesis, and of the vitamins biotin and thiamine (Mengel & Kirkby, 1987). Sulphur is also present within glucosinolates, which are commonly found in Brassica species and which are synthesized from amino acids. Oilseed rape has a larger requirement for S than other arable crops because S is required for the formation of both proteins and glucosinolates. Where S is in short supply, protein synthesis is maintained at the expense of glucosinolate synthesis (Josefsson, 1970; Schnug, 1987b), although it is common to get an increase in both when S is applied.

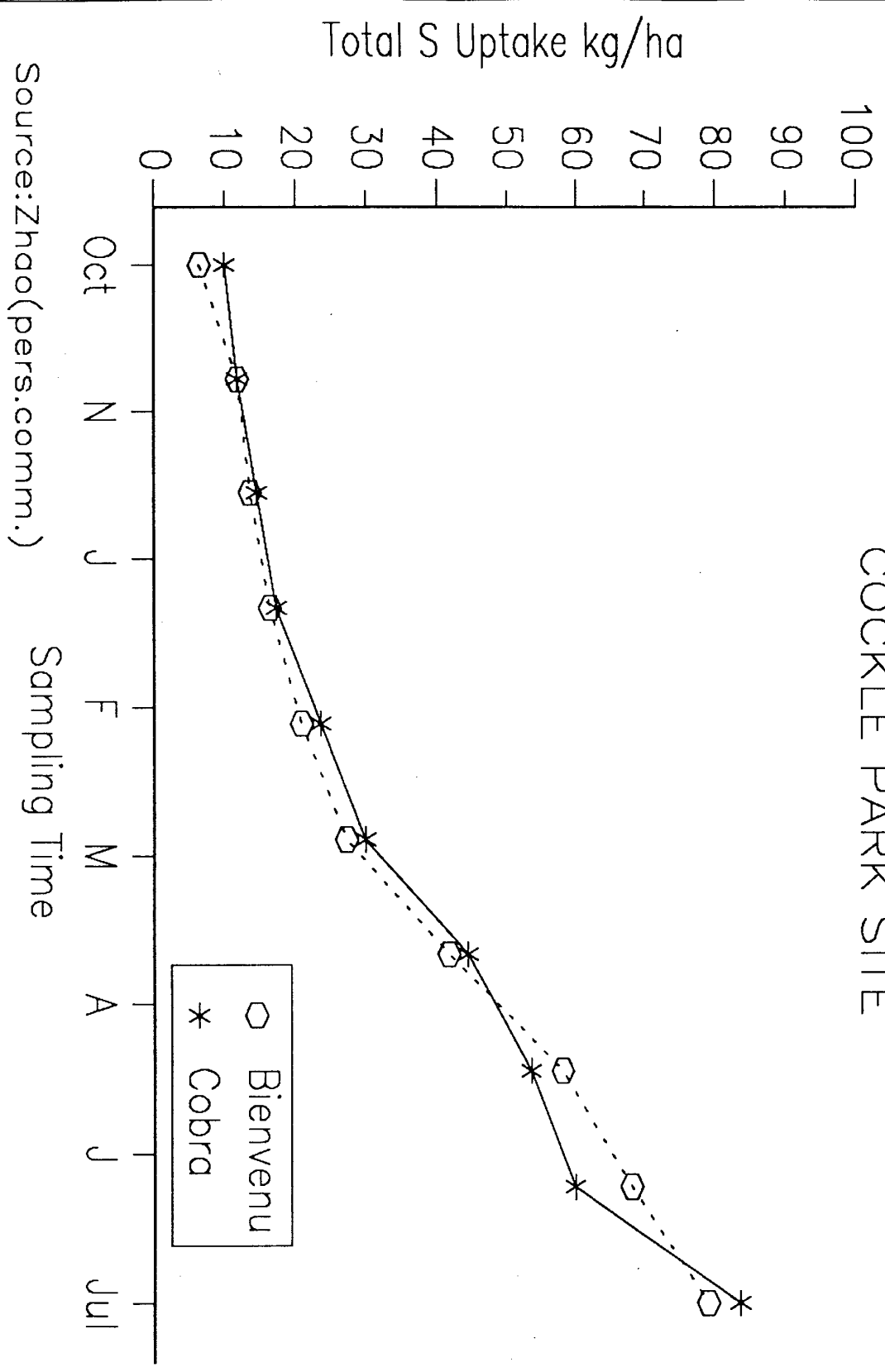
The uptake of S by a crop yielding 3 t/ha of seed is usually between 45 and 70 kg/ha ( McGrath & Johnston, 1986; Syers et al., 1987; Merrien et al., 1988; Klessa & Sinclair, 1989), although uptakes as large as 100 kg S/ha have been achieved (F.J. Zhao, pers. comm.). Removal of S in the seed at harvest is typically 20-30 kg/ha, depending partly on yield level. Although the seed offtake in double low varieties is up to 10 kg S/ha less than for single low varieties, because of their smaller seed glucosinolate content, their total requirement for S is the same (Schnug, 1987a; Merrien et al., 1988) (Fig. 5). Once taken up by the plant, S is not readily mobilised from older leaves and a constant S supply is required for optimum growth of younger tissues. The complex interaction of factors which contribute to the supply of S to the plant can be summarised by the S cycle (Fig. 6).

In modern oilseed rape production the demand for S, which reaches a maximum at the end of pod growth or harvest, is largely satisfied by S inputs from the soil and the atmosphere. Inputs of S from organic manures, which are extremely variable in their S content, and from certain fertilisers which are now little used (single superphosphate, ammonium sulphate) are often negligible on arable farms. Where inputs of S from the atmosphere are lower than the S output in the harvested seed, the soil reserves of S gradually become depleted and clearly there will at some point be a need for S fertilisation depending on the size of the soil S pool. The contribution of S from the soil and the atmosphere is discussed below:

i)      Soil S

Sulphur in all agricultural soils is largely contained within the soil organic matter and must be released by microbial mineralisation before being absorbed by the plant roots as sulphate ( $\text{SO}_4\text{-S}$ ). The effectiveness of the mineralisation process in providing sufficient S for plant uptake depends not only on optimal soil moisture, temperature and pH conditions for microbial activity but also on whether the soil organic matter will act as a source of S (i.e. net

Fig.5 SULPHUR UPTAKE OF BIENVENU AND COBRA  
COCKLE PARK SITE



Source:Zhao(pers.comm.)

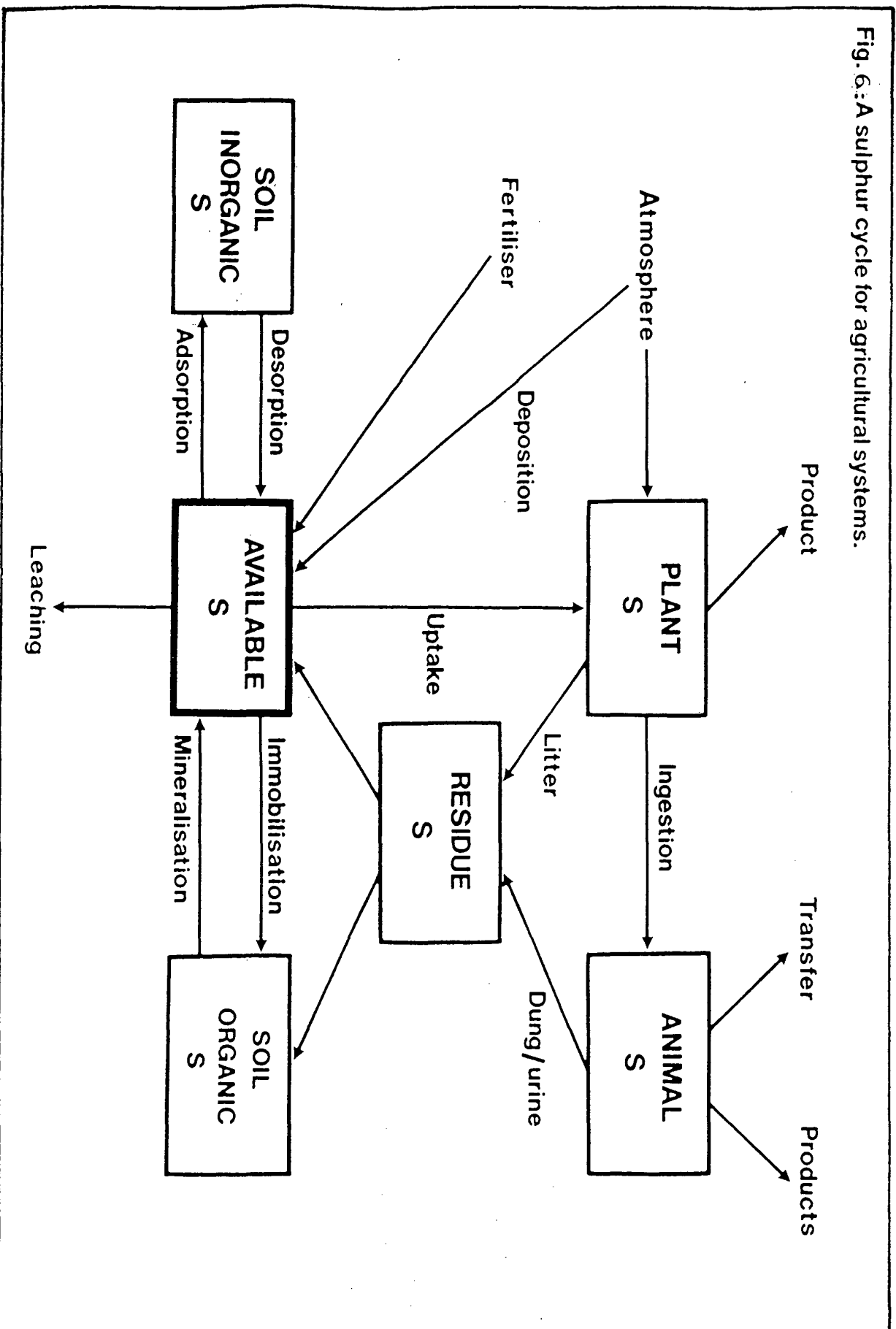


mineralisation of S as organic matter levels decline) or as a sink for S (i.e. net immobilisation of S as organic matter levels increase). In continuous arable cultivation where organic matter levels are low and inputs of organic substrate with a satisfactory C:N:S ratio are negligible, net mineralisation of S probably makes only a small contribution to the S pool available to the plant (Syers et al., 1987). As with N, periods of net mineralisation are most likely in autumn and spring.

The  $\text{SO}_4\text{-S}$  released through mineralisation, or added to the soil from the atmosphere or by fertiliser application, is weakly adsorbed onto clay and iron oxide surfaces in the soil (Syers et al., 1987). This reservoir of adsorbed  $\text{SO}_4\text{-S}$  supplies the soil solution from which plants take up S. Soil solution  $\text{SO}_4\text{-S}$  which is not taken up by roots in the transpiration stream is leached out of the soil. The mobility of  $\text{SO}_4\text{-S}$  is probably slightly less than that of nitrate especially in soils with a high iron oxide content but significant amounts of  $\text{SO}_4\text{-S}$  leaching can occur, especially on sandy soils in areas of high winter rainfall. Studies on grassland have indicated that the amounts leached can be as large as the amounts taken up (Bristow & Garwood, 1984). Similarly, the S added in winter rains is thought to contribute little to crop uptake on well drained soils since crop demand is low at this time and the leaching risk is high.

The adsorption capacity of the soil is therefore critical to the availability of  $\text{SO}_4\text{-S}$  to the plant especially during periods of rapid uptake after stem extension stage. In the U.K. the capacity of topsoils to adsorb  $\text{SO}_4\text{-S}$  has been shown to be very low, especially at pHs above 6.0 (Curtin & Syers, 1990) except on soils with a high iron oxide content. Agronomic inputs such as lime and phosphate fertiliser reduce the capacity of the soil to absorb  $\text{SO}_4\text{-S}$ , although this is less of a problem in the subsoil where adsorption capacity is thought to be greater. Amounts of available  $\text{SO}_4\text{-S}$  are considerably higher in heavier-textured subsoils (Withers - unpublished data) but there is insufficient information on the extent to which plants can utilise  $\text{SO}_4\text{-S}$  in the subsoil. Although the root system of oilseed rape has been shown to reach a depth of 1.8 metres, the majority of roots are concentrated in the top 40 cm (Barracough, 1989).

Fig. 6: A sulphur cycle for agricultural systems.



Source : Syers et al. (1987)

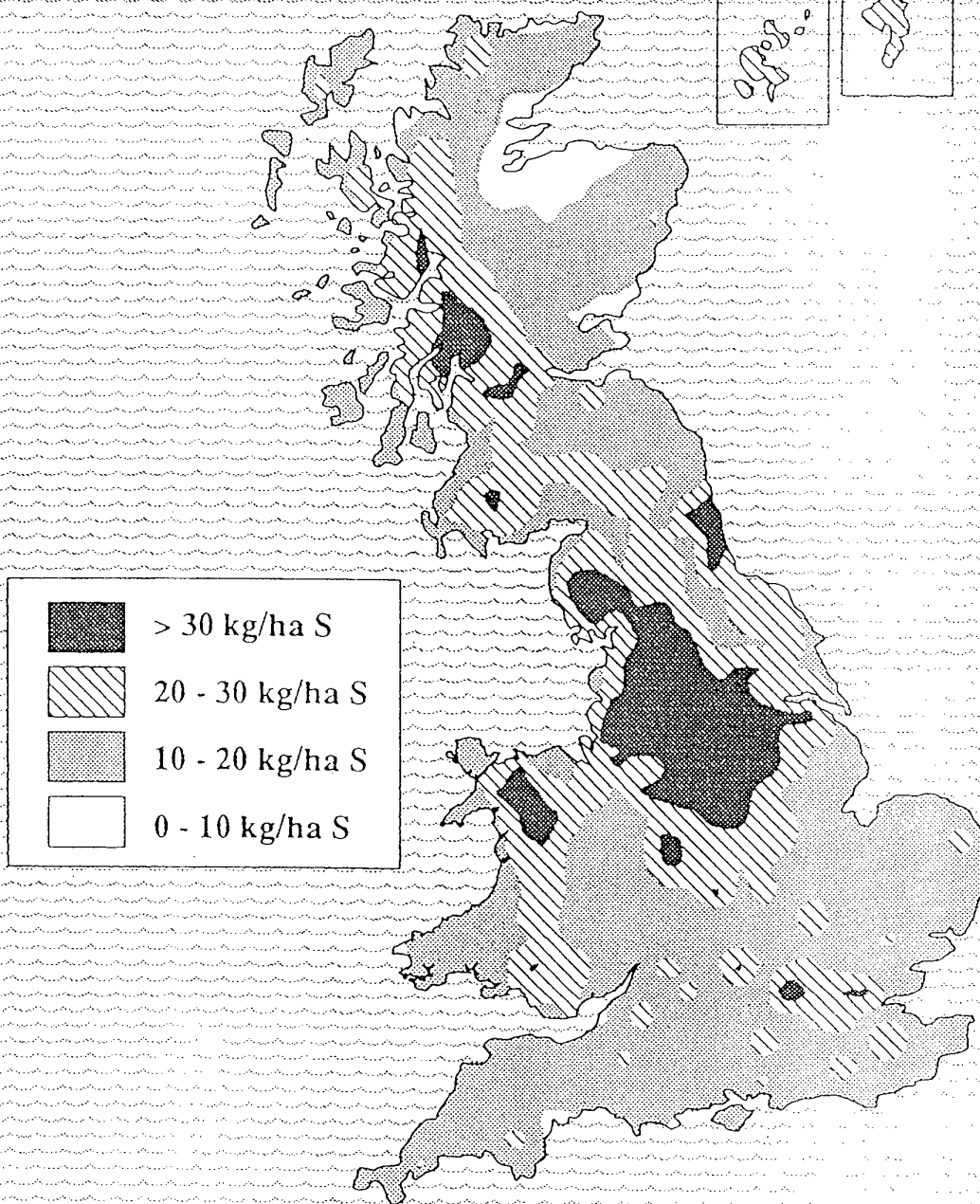
## ii) Atmospheric S

Sulphur is deposited from the atmosphere in both gaseous form (dry deposition) and in rainfall (wet deposition). The amounts deposited vary from less than 15 to over 40 kg S/ha/year, depending on location and nearness to industrial activity (Fig. 7). On western coasts, sea spray can also contribute to wet deposition, by as much as 15 kg S/ha/year (Skinner, 1985). Substantial amounts of S can be deposited in high rainfall areas away from industrial activity but in the main oilseed rape growing areas in Eastern and Central England, dry deposition is the major atmospheric input of S.

Gaseous sulphur dioxide accounts for the majority of the total amount of S deposited in the U.K. and on soils of poor S status up to 50% of the crop's requirement can be taken up in the gaseous form. Even on soils with adequate S reserves, plants will still take up sulphur dioxide by diffusion through stomata. The amounts taken up by plants depends on the concentration of S dioxide in the atmosphere and the rate at which it is delivered to the leaf surface (Skinner, 1985). Sulphur dioxide concentrations are higher in winter due to greater domestic power consumption whilst in summer diurnal fluctuations can be significant, being highest at midday when stomata are fully open. For oilseed rape, the need for a S supply from the atmosphere is probably greatest in early spring when the crop starts growing before soil temperatures have risen sufficiently for mineralisation of organic matter to help maintain the supply of  $\text{SO}_4\text{-S}$  to the soil solution.

The main source of atmospheric S is the burning of fossil fuels by the electricity industry but emissions of sulphur dioxide have been steadily declining since the late 1960's and 1970's (Roberts & Fisher, 1985; Anon, 1987d). With a commitment by the electricity industry to further reduce industrial emissions of sulphur dioxide by 60% by the year 2012, the need for S fertilisation to prevent yield loss will increase. The importance of atmospheric deposition in sustaining crop yields has been demonstrated in experiments by

Fig. 7. **TOTAL ANNUAL  
SULPHUR DEPOSITION**



Information supplied by Warren Springs Laboratory 1990

Bristow & Garwood (1984) where grass yield and herbage S concentrations fell annually from 1979 to 1982 in response to falling mean concentrations of atmospheric S.

### 6.3 Deficiency

Consideration of the supply of S from the soil and the atmosphere make it clear that S deficiency in oilseed rape is most likely to occur in areas of low atmospheric deposition and on well drained sand and chalk soils which have a low capacity to mineralise and/or adsorb and retain S.

Symptoms of severe S deficiency usually appear as distinct interveinal chlorosis of the upper and middle leaves from stem extension onwards, but have been reported in autumn. If left untreated, the crop gradually becomes stunted, produces a very pale inflorescence and pod set is poor. Deficient crops often flower later and produce fewer pods, with seed in established pods failing to develop normally. With severe deficiency, the length of the flowering period can be reduced. A characteristic feature of S deficiency is that it occurs in random patches across the field and it is quite common to find a deficient plant alongside a perfectly healthy plant. Deficient areas are especially noticeable from a distance. The total S content of leaves showing deficiency symptoms is typically less than 3-3.5 g/kg (Schnug, 1989; Withers, 1989) or less than 250 mg/kg water extractable  $\text{SO}_4\text{-S}$  (A.H. Sinclair, pers. comm.).

Symptoms at flowering may occur without leaf symptoms appearing and yield responses to application of S fertiliser have been obtained without any symptoms appearing in untreated plots. Advisory experience suggests that leaf symptoms are indicative of more severe deficiency and often coincide with periods of very cold dry weather or where rooting is poor due to late emergence, or where spring rains have leached available  $\text{SO}_4\text{-S}$  below the rooting zone. For example, prolonged dry topsoil conditions and in generally poor root development in 1991 induced S deficiency in oilseed rape on a range

of soil types, including those on which deficiency would be less likely. Crop symptoms disappear quickly when adequate S fertiliser is applied to the crop (Janzen & Bettany, 1986), although application of fertiliser S may not compensate fully for the natural S release which would be obtained from a soil well supplied with S (Booth et al., 1991).

#### 6.4 Yield Response

Yields of spring oilseed rape were increased by up to three-fold with the application of 22 kg  $\text{SO}_4$ -5/ha on deficient soils in Canada (Nyborg & Bentley, 1971; Nyborg et al., 1974) but other experiments in Canada (Anderson & Kusch, 1968) did not however show any response to S at that time. Field experiments on spring oilseed rape between 1973 and 1976 (Holmes & Ainsley, 1977) and on winter oilseed rape between 1974 and 1976 (Holmes & Ainsley, 1978) failed to show any yield benefit from 50 kg S/ha applied as single superphosphate to the soil at sowing. A number of experiments carried out by ADAS between 1981 and 1987 on potentially S deficient soils also showed mostly no response to S which was applied either as gypsum or as micronised elemental S (Syers et al., 1987). Small yield responses had been obtained at a very small number of sites on shallow chalk soils but effects were not consistent. The first large significant yield response (+ 0.5t/ha) to applied S (50 kg/ha) in oilseed rape in either England or Wales was in Cumbria in 1987 on a stony loamy sand soil (Withers, 1988). Typical deficiency symptoms of pale inflorescence were seen for the first time at this site. In Scotland, where atmospheric S inputs are much lower than in England and Wales, deficiency symptoms and associated yield response had been noted since 1984 (Anon, 1984).

Further ADAS experiments since 1987 have continued to show large yield responses (up to 0.83 t/ha) in oilseed rape (Withers, 1989) and recent trials in Scotland have shown yield increases of over 300% with greater response in double low varieties than in single low varieties when grown at the same site (Booth et al., 1991). These results clearly indicate that the frequency of yield response to S

fertilisation is increasing, especially since the introduction of double low varieties, as atmospheric S levels continue to decline. This conclusion is also supported by the observation that S deficiency symptoms are becoming more widespread, especially in Northern England (Evans et al., 1991). However the expression of yield response depends largely on the season, even on soils which are known to be S deficient. Variation in yield response between sites of similar S status may also be due to differences in the action of S fertiliser within the soil (Schnug, 1991b).

Experiments in France have shown that an application of 30 kg S/ha, applied at the start of spring growth, increased yield on average by 0.35 t/ha in 8 years out of 10 (Merrien et al., 1987). Field experiments carried out between 1979 and 1986 in Germany showed yield responses as high as 11% from 100 kg S/ha applied in early spring as elemental S (Schnug, 1987a). Much higher yield responses have regularly been obtained on S deficient soils in Canada (Nuttall et al., 1987). Sulphur deficiency is now recognised as a significant yield limiting factor in European agriculture (Schnug, 1991a).

## 6.5 Diagnosis and Treatment

In Scotland analysis of the available S content in the soil, using the method developed by Scott (1980), is still used to assess the risk of S deficiency and yield response (Table 19). This system has not however been found to be a satisfactory method of prediction elsewhere in the U.K. (Syers et al., 1987). In France, soil analysis according to the Scott method in early spring has been used to distinguish between sites likely to respond to S fertilisation (A. Merrien, pers. comm.). Sites with less than 18 mg  $\text{SO}_4\text{-S}$ /kg soil were responsive and further work is underway to examine the effects of time of sampling on soil  $\text{SO}_4\text{-S}$  content. The unreliability of soil  $\text{SO}_4\text{-S}$  measurement is perhaps not surprising when one considers the heterogeneous nature of soil S release and the patchy distribution of S deficiency in fields, also the fact that  $\text{SO}_4\text{-S}$  contents in the subsoil are not taken into account.

Table 19. Classification and interpretation of the S status of soils in Scotland

Extractable S (mg/1 air-dry soil, <2mm)	Status	Interpretation
<3.0	VL (Very Low)	Response to applications of S likely in sensitive crops.
3.0-6.0	L (Low)	Response possible in sensitive crops.
6.1-10.0	M (Moderate)	Response unlikely except in oilseed rape grown in areas where atmospheric supply of S is low.
>10.0	H (High)	Toxic effects possible at very high levels.

Source: A. H. Sinclair (pers. comm.)

The measurement of  $\text{SO}_4\text{-S}$  to in the soil to 90 cm depth may well provide a better estimate of plant S status but, as with N will need to be taken at specific times of the year. In Ireland available  $\text{SO}_4\text{-S}$  in soil is being incorporated into a model to predict the need for S fertilisation, but soil texture and organic matter content were more useful in predicting S response in grass (Murphy, 1990). Soils with more than 50% sand and less than 3% organic carbon were found to respond to S fertiliser.

Plant analysis has been shown to be a better indicator of response than soil status in England and Wales (Withers, 1989) and good correlation between yield response and plant S status have been developed in Europe (Schnug, 1987b). In Germany, total S contents of at least 6.5 g/kg in the leaves at stem extension stage are considered necessary to obtain 90% of maximum yield. In France total S concentrations below 5 g/kg at the stem extension to closed bud stages are considered sub-optimal for yield (Merrien, pers. comm.) and this figure is commonly used in England (Evans et al., 1991). However values below this have been obtained in a number of ADAS trials with no yield response (Withers, 1989). In Canada, total S content in leaves at the rosette stage was shown to be less useful



than the ratio of organic S:inorganic S in the leaf, which was unaffected by crop N supply (Maynard et al., 1983).

In the U.K., the leaf N:S ratio has proved useful in predicting yield response in a range of crops (Syers et al., 1987; Klessa & Sinclair, 1989), including oilseed rape (Withers, 1989). N:S ratios greater than 13:1 and especially above 17:1 are usually but not always indicative that a yield response will occur to applied S. Leaf  $\text{SO}_4\text{-S}$  concentrations at flowering below 1 g/kg were indicative of yield response in recent ADAS trials (Withers, 1989) but are thought to be too sensitive to rapid fluctuations in plant growth or to the presence of other nutrients in the soil solution (Syers et al., 1987).

The amount of S fertiliser required for maximum yield response is still under investigation but has been shown to vary between 20 and 75 kg S/ha (Withers, 1989). In North-east Scotland, single and double low varieties receiving 250 kg N/ha showed a yield response up to 64 kg S/ha (applied as elemental S) but only responded up to 32 kg S/ha when 150 kg N/ha was applied (Booth et al., 1991). This effect of larger N rates accentuating S deficiency has also been observed by other workers, as discussed below.

The effectiveness of different forms of S fertiliser has been the subject of a number of investigations. There is general agreement that sources of soluble  $\text{SO}_4\text{-S}$  (potassium sulphate, ammonium sulphate, magnesium sulphate) are rapidly available after application and have invariably given the largest yield response in a number of ADAS experiments (R.J. Skinner, pers. comm.). Although soluble sources of  $\text{SO}_4\text{-S}$  are rapidly available they are also subject to leaching and have very little residual value (Rhue & Kamprath, 1973). Partially soluble calcium sulphate (gypsum) was shown to be as effective as more soluble  $\text{SO}_4\text{-S}$  forms in increasing yield (Withers, 1989). Sulphur applied as thiosulphate has been shown to be rapidly oxidised and comparable to soluble  $\text{SO}_4\text{-S}$  in its short term release pattern (Jansen & Bettany, 1986). On a S deficient site in Dorset in 1988 this source of S, applied as a foliar spray (8 kg S/ha) gave a

significantly lower yield than potassium sulphate applied to the soil (30 kg S/ha). However the discrepancy between the rates applied is probably significant, assuming the amount of direct leaf absorption of thiosulphate is as low as for elemental S.

Recent trials in Scotland have shown that applications of micronised elemental S can be very effective in increasing yields on S deficient sites when applied in adequate quantity (Booth et al., 1991).

Elemental S is most commonly applied as a foliar spray and has been shown to be less effective than foliar soluble  $\text{SO}_4\text{-S}$  when applied at the same rate and time (Table 20). Higher application rates of elemental S however were more effective.

Table 20. The effectiveness of rate and timing of foliar applications of soluble sulphate and elemental sulphur in cv. Ariana

Treatment (kg S/ha)		Seed Yield (t/ha, 91% DM)		Glucosinolate ( $\mu\text{mol/gram}$ )	
With 1st N (17 March)	With 2nd N (21 April)	Sulphate-S	Elemental S	Sulphate-S	Elemental S
-	-		1.75		8.7
7	-	3.07	2.64	8.0	8.5
-	7	3.16	2.79	8.9	9.9
14	-	3.24	3.14	8.0	11.0
-	14	3.20	3.14	7.8	11.6
7	7	3.55	3.07	11.0	9.6
14	14	3.27	3.45	11.7	13.2

Sulphate-S was applied as Chafers 35N + 2.5% S

Elemental-S was applied as Thiovit (80% S)

Source: A. H. Sinclair (pers. comm.)

The amount of elemental S absorbed in this form by the crop has been shown to be less than 2% of that applied in experiments using radioactively-labelled micronised S (McGrath & Johnson, 1986). Most of the elemental S applied to the foliage is washed into the soil by rain falling after application and its effectiveness depends on the activity of the microbial populations (especially *Thiobacillus*) which oxidise elemental S to  $\text{SO}_4\text{-S}$ . The populations of these micro-organisms may be low where S compounds have not been regularly used and their activity is subject to fluctuations in soil moisture and temperature conditions. The availability of elemental S applied to the soil also depends to a large extent on the initial particle size of the fertiliser and its adequate dispersion into the soil (Janzen & Bettany, 1986). For example, mixtures of molten elemental S and sodium bentonite applied in prill form were ineffective compared to ammonium sulphate because of inadequate dispersion in the soil (Nuttall *et al.*, 1987), whereas micronised S of particle size 325 mesh were rapidly oxidised to  $\text{SO}_4\text{-S}$  (Janzen & Bettany, 1986).

In view of the mode of action of foliar applications of micronised S, it is now recognised that the poor yield responses obtained with this form of fertilisation in the past are probably due to either inappropriate timing or amounts applied (the recommendation was to apply 8 kg S/ha at stem extension). Larger application rates have since shown to be effective in controlling S deficiency provided they are applied early to maximise the amount of  $\text{SO}_4\text{-S}$  released in the first year of application. The amounts released in the first year will affect their residual value, this may become more important in the future as cereals succumb to S deficiency. Oxidation of elemental S also causes soil acidification, however normal lime losses from soil will decrease as sulphur dioxide deposition continues to decline. If the net S input results in a lowering of soil pH, this would increase the availability of other trace elements (Schnug, 1987a) and the need for lime application.

Table 21. Composition of some S-containing fertilisers

Fertiliser	Composition (%)				
	S	N	P	K	Other
Elemental S	80-96	-	-	-	
Ammonium sulphate	24	21	-	-	
Kieserite	23	-	-	-	
Potassium sulphate	20	-	-	50	
Gypsum	18	-	-	-	
Manganese sulphate	14	-	-	-	Mn (25)
Magnesium sulphate	13	-	-	-	Mg (10)
Single superphosphate	12	-	20	-	
Copper sulphate	11	-	-	-	Cu (25)
Ammonium phosphate	3	11	48	-	
Triple-superphosphate	1	-	40	-	

Source: Klessa & Sinclair (1989)

The handling qualities of S fertilisers must also be taken into account when deciding on a suitable source of S. Most sources of soluble  $\text{SO}_4$ -S contain other useful major nutrients (Table 21) although these may not always be wanted and can make the fertiliser prohibitively expensive for widespread agricultural use (e.g. potassium sulphate). Gypsum is a powder and difficult to spread. Ammonium sulphate is the most economic method of applying S but at the rates required (20-30 kg S/ha) supply only a small amount of N. This form of soluble  $\text{SO}_4$ -S is also very hygroscopic and can be difficult to spread in wet weather.

Pot trials in Germany have indicated that the timing of soluble  $\text{SO}_4$ -S sources may be manipulated to minimise increases in seed glucosinolates yet maintain optimum yield response (Schnug, 1987b). Applications of potassium sulphate during stem extension lowered glucosinolate contents by 70% in both single low and double low

varieties compared to application at sowing but yield response was unaffected. However, application at or after flowering not only significantly reduced yield in double low varieties but also caused dramatic increases in glucosinolate contents. In contrast to this, foliar applications of magnesium sulphate at flowering have been shown in recent field trials in Germany to be as effective yield-wise as any other method of application and only changed seed glucosinolate content slightly. Application rates of 10-12 kg S/ha were optimal and did not appear to cause any physical damage to the crop (Anon, 1990). Under conditions of severe S deficiency, maximum recovery of yield is most likely to be achieved from earlier (eg rosette stage) rather than later applications (Janzen & Bettany, 1984b).

Current advisory recommendations in the U.K. for oilseed rape grown in potentially S deficient situations is to apply 20-30 kg S/ha as soluble  $\text{SO}_4\text{-S}$  at the start of growth in the spring. In Scotland, where the response to S in winter oilseed rape is now widespread, recommendations for S treatment are the same for both autumn and spring sown crops (Anon, 1985c). Similar recommendations apply in Europe (Merrien, pers.comm.; Anon, 1990). The effectiveness of larger amounts of elemental S applied in early spring and of foliar applications of soluble  $\text{SO}_4\text{-S}$  at the flowering stage require further evaluation under U.K. conditions.

## 6.6 Sulphur and Seed Quality

### i) Oil Content and Composition

Experimental evidence indicates that the effect of applications of S fertiliser on seed oil content varies according to the season but that seed oil content is decreased by S application more often than it is increased. Sulphur applications were shown to increase seed oil content of double low varieties at over 90% of sites in Canada (Nuttall et al., 1987), but exactly the reverse was found by Wetter et al. (1970) working with single low varieties. In experiments in England and Wales between 1985 and 1988, 50 kg S/ha applied as gypsum reduced oil content by about 1% in six out of fourteen sites although

these were mostly on non-responsive sites and confined to single low varieties in 1985 (Withers, 1988). Applying S reduced oil content at a further 1989). Work carried out by Appelqvist (1968) suggested that S fertilisation affected the fatty acid composition of the oil, with lower contents of erucic acid and higher contents of oleic acid in S deficient seed, but effects appear to depend on variety (Randall & Wrigley, 1986). Variety was also shown to have a greater influence on fatty acid composition than the location in which the crop was grown (Craig & Wetter, 1959).

## ii) Glucosinolates

Up to one hundred different glucosinolates are known to occur within the family Cruciferae, but only about thirty have been identified in the genus Brassica (Fenwick *et al.*, 1986). Three main types of glucosinolate occur in oilseed rape, depending on the nature of the R group (Table 22).

Table 22. Main groups and most common forms of glucosinolate in oilseed rape

Alkyl R (Aliphatic)	Indole R (Indolic)	Phenyl R (Aromatic)
Gluconapin	Glucobrassicin	Gluconasturtin
Glucobrassicinapin	Neo-glucobrassicin	
Progoitrin	4-OH glucobrassicin	
Gluconapoleiferin		

Indolic and aromatic glucosinolates are often grouped together and an additional Thio R group has been identified by Merrien & Ribaillier (1988).

These glucosinolates, which are synthesized from amino acids, co-exist in all parts of the plant along with a glucosinolate-splitting enzyme called myrosinase. Cell culture experiments have

shown that in the absence of an adequate S supply, glucosinolates can be broken down by myrosinase to provide  $\text{SO}_4\text{-S}$  (Underhill, 1980). This response to S stress is thought to be inhibited in double low varieties because of their lower glucosinolate content. This feature prompted Schnug (1987) to suggest that double low varieties may be more susceptible to S deficiency and indeed this has been shown to be the case under U.K. conditions (Booth et al., 1991).

The S content of glucosinolates is approximately 15% and recent experiments indicate that about a quarter to a third (25-35 kg/ha) of the S in the crop is in glucosinolate form (G.M. Milford, pers. comm.). Consequently S nutrition of oilseed rape has a large influence on the glucosinolate concentration in rapeseed at harvest. As far back as 1959 differences in glucosinolates were reported, depending on where the oilseed rape was grown (Craig & Wetter, 1959), and Josefsson (1970) found that fields with light textured soils gave seed samples with significantly lower glucosinolate contents than samples from other fields. Recent crop surveys in Northern Britain have also shown this effect for double low oilseed rape crops (Evans et al., 1991). Crops with low contents of S as a result of low atmospheric deposition and poor soil S supply have produced seed with low glucosinolate concentrations. Sulphur was the predominant factor affecting the glucosinolate content of double low variety seed in over seven hundred crops in Schleswig-Holstein when the effects of single low and cruciferous weed volunteers were excluded (Schnug, 1989).

It is now well established that application of S fertilisers increases seed glucosinolate concentrations (Josefsson, 1970; Wetter et al., 1970; Nuttall et al., 1987; Merrien & Ribaillier, 1988; Milford & Evans, 1991) and that the increase in glucosinolates is much higher in single low varieties than in double low varieties (Schnug, 1987b; Booth et al., 1991). However with double low varieties, S fertilisers give larger increases in glucosinolates at some sites but not others (Nuttall et al., 1987; Withers, 1989; Evans et al., 1991). Experiments to date indicate that the lower the crop S content, the greater the increase in seed glucosinolates from S

fertilisation. For example, increases of 2-3  $\mu\text{mol}/\text{gram}$  at sites well supplied with S and increases of 8-9  $\mu\text{mol}/\text{gram}$  at sites of poor S supply are often obtained from 50 kg/ha applied S (Withers, 1989; Evans *et al.*, 1991). Large increases in seed glucosinolates are usually accompanied by a yield response (Wetter *et al.*, 1970; Nuttall *et al.*, 1987; Withers, 1989; Booth *et al.*, 1991) but not always so (A. Merrien, *pers. comm.*; Evans *et al.*, 1991).

There is little doubt that the effect of S fertilisation and plant S content on seed glucosinolate content at harvest is modified by seasonal and other factors, and that the interaction between them remains poorly understood (Milford & Evans, 1991). The use of high rates of N have been shown to increase the severity of S deficiency and the magnitude of yield response to S fertilisation (Janzen & Bettany, 1984a; Booth *et al.*, 1991). It is not however clear whether this is due to a reduced S uptake, as suggested by Janzen & Bettany (1984a) or a simple dilution of the plant S content. The effect of this N x S interaction on seed glucosinolate content is that:

- a) At S deficient sites, increasing the N rate can decrease seed glucosinolate concentration (Booth *et al.*, 1991; Milford & Evans, 1991).
- b) At low N rates, S application has a smaller effect on the increase in glucosinolate content (Milford & Evans, 1991) or the rate at which glucosinolate concentrations increase (Booth *et al.*, 1991).

Substantial differences in seed glucosinolate content are known to occur between seasons, especially on chalk soils, and between different branches in the same crop or between different parts of the same plant (Milford & Evans, 1991). Within - field variation may result partly from the heterogeneous supply of S that is typical of the soil S cycle, the S status of individual plants is also known to show similar variation (Anon, 1988), not least in the form that S deficiency symptoms take. Field seed samples will also differ significantly depending on the level of single low volunteers and



cruciferous weeds (Schnug, 1989) but this is a factor which to some extent is under the farmer's control. Merrien & Ribaillier (1988) argued that the seasonal factors that affect seed glucosinolate concentration find expression in the components of yield (seed number/ha and seed size) and that it is the distribution of plant S between these seeds which governs the final glucosinolate concentration in the seed. Where S supplies are low and seed number high (i.e. small seed size), the final glucosinolate content of the seed will be low. A better understanding of the relationship between S supply, seed number, size and glucosinolate content is required.

At a particular site, variation in leaf or plant S content accounts for a large proportion of the variation in seed glucosinolate content. However the use of this correlation between sites is complicated by a number of other factors (Milford & Evans, 1991). In Germany though, leaf analysis for total S at the stem extension stage has shown good correlation with final seed glucosinolate concentration (Schnug, 1987c; Anon, 1988) and the accuracy of this means of prediction is currently the object of further research work.

## 6.7 Conclusions

1. Double low varieties are more susceptible to S deficiency than single low varieties. Atmospheric S levels have also declined substantially in recent years. Both these factors have led to an increased incidence of S deficiency in oilseed rape.
2. Severe S deficiency produces characteristic symptoms of leaf chlorosis, restricted flowering and poor pod set. Sulphur concentration in deficient leaves are typically below 0.35% S but the crop S content below which a yield response might be expected remains unclear.
3. Crop S status is primarily determined by soil type and location and deficiency is most likely to occur on sandy soils in continuous arable production, in areas receiving less than 20 kg S/ha/annum. The interaction between soil S supply and crop

uptake governs the extent to which deficiency occurs in any one season.

4. Soil S supply is governed by the conflicting processes of mineralisation and immobilisation during organic matter turnover, by adsorption of released  $\text{SO}_4\text{-S}$  onto soil colloid surfaces and by leaching of available  $\text{SO}_4\text{-S}$  by winter rains. The interaction between these processes for different soil types remains poorly understood and quantified as is the contribution of S supply from the subsoil to total plant S uptake.
5. Crop S supply has a primary but poorly understood influence on the production and accumulation of glucosinolates during crop growth and development. The glucosinolate concentration in the seed at harvest however depends not only on S supply but also on the extent to which this has been modified by other factors such as seed number and seed size. A better understanding is required of the relationships between S supply, seed number, seed size and seed glucosinolates.
6. The application of S fertiliser has a dramatic effect on crop yield where crop S supply is deficient. Applications of soluble  $\text{SO}_4\text{-S}$  have proved more effective than elemental-S fertilisers (either applied as a folial spray or direct to the soil) when applied at the same rate and time. The effectiveness of elemental S fertilisers is greatly influenced by their particle size and the ability of the microbial population in the soil to oxidise the S to  $\text{SO}_4\text{-S}$ . The optimum rates and timings of soluble and elemental S fertilisers and their residual value needs to be more precisely quantified.
7. Sulphur fertilisation gives relatively large increases in glucosinolates at some sites but not others. Large increases are not always associated with yield responses but tend to occur where crop S supply is poorest. The influence of soil type on glucosinolate concentration requires further investigation.

8. The heterogeneous nature of soil S supply cannot be satisfactorily quantified by field trials based on simple randomised block design. It is recommended that alternative designs are incorporated into future research proposals to minimise the error associated with the spatial variability of soil S release.

## 7. TRACE ELEMENTS

### 7.1 Introduction

In recent years, increasing emphasis has been placed on the trace element (also known as minor nutrient) nutrition of arable crops including oilseed rape. Applications of organic manures have declined on the arable farm and high crop yields are being achieved and maintained by the use of increasingly specialised fertilisers. The ability of soils in continuous arable production to supply the trace element demands of crops has therefore become more important although atmospheric inputs of trace elements can be significant, especially near the coast and in areas of industrial activity (Archer, 1985).

Oilseed rape has largely been grown on heavier-textured soils since its introduction as a major break crop during the 1970s but is now increasingly being grown on a wider range of soil types (Bowerman et al., 1990), some of which are less suited to arable cropping, including those with inherently low trace element supply. So far trace element deficiency problems have not been widely reported in oilseed rape grown on these nutrient poor soil types, indicating that the crop is not unsuited to these situations.

Before detailing the specific trace element requirements of oilseed rape it may be useful to detail a number of generally accepted features of trace element chemistry which are common to all crops:

- a) Trace elements are required by crops in only small amounts compared to the major nutrients. Plant uptake is usually measured in g/ha rather than kg/ha.
- b) Trace element contents of different soils vary depending on the parent material from which they were formed but are usually lowest in soils derived from acid igneous rocks and sands.

- c) Soil solution concentrations of trace elements are primarily determined by the ease of weathering of the primary minerals of which they are a part but are subsequently modified by a number of soil and crop factors: soil pH, organic matter, surface absorption, microbial activity, crop rooting density, nutrient uptake and release of organic substances from plant roots. Maximum mobilisation of trace elements has been shown to occur in the rooting zone during the period of maximum growth in the spring (Sinclair et al., 1990)
- d) Trace element deficiency is referred to as 'clinical' when specific symptoms appear in a crop or 'sub-clinical' (latent or hidden) when no symptoms develop but the crop responds to trace element fertilisation. Crop symptoms may persist (acute deficiency) or disappear naturally (transient deficiency) and can be confused with one another and with those caused by drought, severe frost or herbicide damage.
- e) It is common practice in the U.K. to identify critical concentrations of trace elements in plants and soils associated with clinical deficiency. However yield loss can still occur above such critical concentrations and in mainland Europe, threshold plant concentrations for deficiency are those below which less than 90% of crop yield is achieved. Such values are obtained not by appearance of deficiency symptoms but by assessment of crop performance on different soil types.
- f) It is now generally accepted both within the commercial sector and advisory bodies that advisory recommendations should be based on the principle that an application of a trace element fertiliser is required only where a specific deficiency has been identified by soil and/or plant analysis (Table 25). High yielding crops are not necessarily more prone to trace element deficiencies than lower yielding crops (Sinclair et al., 1990).

Although many trace elements are essential for satisfactory crop growth only six have been shown to become yield limiting in

agricultural crops in the U.K.; boron (B), manganese (Mn), copper (Cu), iron (Fe), molybdenum (Mo) and zinc (Zn). There is only very limited information on the trace element requirements of double low varieties compared to single low varieties. Double low varieties have been shown in experiments to take up larger amounts of trace elements than single low varieties although this was not necessarily reflected in increased grain offtake, especially in the case of manganese (Table 23). The relevance of these elements to oilseed rape production is discussed below. The soil chemistry and plant physiology of these elements will only be briefly summarised here, more comprehensive details are given by Mengel & Kirkby (1987), Archer (1985) and Davies (1980). The trace element status of U.K. soils has recently been produced as a Geochemical Atlas (McGrath & Loveland, 1991).

Table 23. Trace element uptake (g/ha) and the proportion (%) removed in the seed for cv Bienvenu (single low) and cv Darmor (double low) yielding 3 t seed/ha

	Uptake (g/ha)		Offtake (% of uptake)	
	Bienvenu	Darmor	Bienvenu	Darmor
Boron	303	324	20	19
Manganese	1653	2080	20	10
Molybdenum	15	18	24	22
Copper	32	46	8	6
Zinc	488	531	57	46
Iron	586	712	49	26

Source: Merrien et al. (1988)

## 7.2 Boron

The behaviour of boron in deficiency situations is the least understood trace element problem affecting oilseed rape production in

the U.K. Deficiencies in field crops of oilseed rape are difficult to diagnose and predict and yield responses to boron fertilisation are inconsistent. In mainland Europe, oilseed rape is considered to have a high demand for boron and deficiency appears to be more widespread. The behaviour of boron in soil and plant is uniquely different to other trace elements and over-application of boron fertiliser can rapidly lead to toxicity (Gupta *et al.*, 1985). Plant and soil boron concentrations appear to vary significantly depending on time and method of sampling.

#### 7.2.1 Crop Requirement

The requirement of oilseed rape for boron has been shown to be between 300-500 g/ha (Bruchlos & Beyme, 1990) with approximately 20% of this uptake being removed in the seed (Merrien *et al.*, 1988). Slightly lower average offtake in the seed of 25-30 g/ha are reported by Szukalski *et al.* (1973) and by Sinclair (1985) from a survey of a small number of oilseed rape crops in Scotland in 1985. Boron is an important structural component of cell walls and appears to have a general regulatory role in plant metabolic processes. A shortage of boron has been shown to interfere rapidly with cell division, cell membrane permeability and often results in phenolic compounds accumulating in plant tissue (Gupta, 1979; Shorrocks, 1991). Boron also has a secondary role in sugar translocation, protein synthesis and auxin metabolism. The largest demand for boron by oilseed rape comes at flowering.

The availability of boron in soil for plant uptake is largely determined by soil pH, texture, organic matter content and moisture (Wear & Patterson, 1962). Strong adsorption of boron onto clay and hydroxide surfaces at more alkaline soil pHs (over 6.5) significantly reduces the availability of boron in the soil solution. In acid to neutral soils, boron is more readily available for uptake (as boric acid) but is easily leached in sandy soils by winter rains. Boric acid does combine with soluble organic compounds in the soil which helps to reduce leaching and improve availability. Deficiency therefore occurs primarily in sandy soils low in organic matter

content, especially if they have been overlimed (MAFF, 1976). It has been suggested that boron deficiency may also occur on highly calcareous soils of moderate to high clay content (Mengel & Kirkby, 1987), this has not however been found in U.K. conditions.

#### 7.2.2 Deficiency

Boron is readily taken up by plants provided soil moisture conditions are adequate. Once translocated, boron becomes relatively immobile and a constant supply is needed for correct growth and functioning of young tissue. Deficiency is therefore almost invariably induced by dry topsoil conditions in soils low in available boron, especially where root growth is poor. Symptoms of boron deficiency in field crops of oilseed rape are very rare both in the U.K. and mainland Europe but have been described in Japan where the deficiency has been known since 1949 (Kanno, 1967). Field symptoms in oilseed rape have been reported in China for many years and are associated with soil boron levels of less 0.2 mg/l (V. Shorrocks, pers. comm.). Boron deficiency in spring oilseed rape has also been reported in Canada (Nyborg & Hoyt, 1970).

Deficiency symptoms first become apparent in youngest leaves as an interveinal purpling extending inwards from the leaf margin. As cell division is disrupted, the crop becomes stunted and brown staining due to phenol accumulation appears in root and stem tissue. Stems become swollen at the base and develop longitudinal cracks; lower leaves become necrotic and brittle and the plant develops a bushy habit due to suppression in growth of the main stem. Flowers show distorted development and petals fall prematurely; pod development is reduced on increased numbers of side branches and seed set is poor (Bergmann, 1983; Shorrocks, 1984; Merrien, 1990).

In the early 1980s in the U.K., stem base swelling and brown stem necrosis were associated with poor yields in a number of oilseed rape crops grown on light sandy soils and shallow calcareous soils over chalk and limestone (Knight, 1980; 1981). Longitudinal stem cracking



also occurs when soil conditions are very dry. Symptoms of brown vascular staining in root tissue and/or failure of the crop to grow are commonly encountered in autumn in the U.K. but usually without leaf discolouration. The extent to which these symptoms are due to boron deficiency is difficult to judge, since plant analysis invariably shows adequate boron levels in root and leaf tissue, and such symptoms can also be found on soils with plentiful supplies of boron.

Experiments in Scotland between 1986 and 1988 clearly showed that symptoms of brown vascular staining in tap roots, and to a lesser extent swelling of stem bases in spring, were significantly lessened by both autumn and spring application of boron fertiliser (Walker, 1988b). However these symptoms never disappeared completely on boron treated plots and it was concluded that whilst such symptoms were characteristic of boron deficiency they could not be used as a method of diagnosis.

Oilseed rape has been shown to develop stem base swelling and necrosis in hydroponic culture when boron is omitted (Reynolds - reported by Shorrocks, 1991). It is interesting to note that only detailed analysis around the affected zone of the plant was able to pinpoint low boron levels compared to healthy plants, and this may be the reason why analysis of the total plant tissue from field crops with similar symptoms indicates a healthy boron status. It has been suggested that these symptoms develop because boron deficiency reduces vacuole membrane permeability sufficiently to allow leakage of compounds into the cytoplasm which subsequently break down to form more harmful substances (phenols, indoacetonitriles) which accumulate in the leaf tissue.

### 7.2.3 Yield Response

The yield response to boron fertiliser applications has been very variable on soils which would be classed as low (MAFF, 1976) or very low (Anon, 1985b) in boron for other susceptible crops at 0.5 mg B/l (hot water extract). The results of experiments to date indicate

that concentrations of available soil boron need to be below 0.5 mg B/l to obtain significant yield responses consistently. In pot experiments in Germany, yield responses were not obtained when soil boron levels exceeded 0.35 mg/l (Gerath et al., 1975). Below this level, yield responses of 5-10% were obtained from application of 1-2 kg B/ha, with treated plants showing greater vegetative growth and more pods than untreated plants. The effects of applying boron were more marked at larger rates of N. Subsequent experiments in Germany (reviewed by Kudryashov, 1986) showed yield responses up to 0.5-0.6 t/ha from boron fertilisation at soil boron concentrations up to 0.4 mg/l but smaller yield responses (0.2-0.3 t/ha) on soils with up to 0.8 mg B/l. In pot trials, significant yield increases of 15% from foliar applications of liquid boron at flowering were obtained, due to increased numbers of large pods with consequently greater numbers of seeds per pod (Zajonc et al., 1985).

More recently, yield responses in twenty four field trials in Northern Germany from 1986 to 1988 averaged 0.2 t/ha from foliar B applications either at stem extension or just before flowering (Bruchlos & Beyme, 1990). In France, yield responses of up to 0.45 t/ha have been obtained on sandy soils with soil boron levels below 0.3 ppm (Cebe, 1988) but a number of experiments, mainly on calcareous clayey soils, showed no response. The latter soils had available soil boron contents as low as 0.2 mg/l and had been shown by leaf analysis to have sub-optimal boron supply in the crop (A. Merrien, pers. comm.).

In the U.K., about thirty trials have evaluated yield response to boron applications in the autumn and spring but at only three sites have there been significant yield responses (Table 24). Small non-significant yield increases were obtained from some treatments at a further four sites, largely in Scotland. In these experiments, boron applications produced more vegetative growth and prolonged the flowering period (Walker, 1988b). However there are still a large number of sites with soil boron levels of 0.5 mg/l and below which did not show deficiency symptoms or any yield response (Withers, 1988). A similar lack of yield response to boron fertilisation on

boron deficient soils has been demonstrated in Poland (Szukalski *et al.*, 1973), Canada (Nuttall *et al.*, 1987) and in France (A. Merrien *pers. comm*). In contrast, substantial yield increases have been reported in field trials in Australia, China, Denmark, Germany, Sweden and the USA (Anon, 1985d), similar responses have been quoted in commercial trials in the UK by Phosyn Chemicals. The effect of season, particularly soil moisture status and susceptibility of treated plots to shedding at harvest, is known to be a contributory factor to the limited occurrence of yield responses to applied boron.

Table 24. Sites with significant responses in seed yield to spring applied boron in U.K. trials, 1980-1988

Year	Site	Soil type	Soil Boron mg/l	Leaf Boron mg/kg	Variety	Control Yield t/ha	Response to Boron t/ha
1980	Kilverstone, Norfolk <sup>1</sup>	Loamy sand pH 7.8	0.53	18	Jet Neuf	2.91	+0.39
1982	Scottton, Lincs <sup>2</sup>	Loamy sand pH 7.6	0.43	12	Jet Neuf	2.86	+0.56
1987	Balspardon, Nairn <sup>3</sup>	-	0.45	18	Mikado	2.99	+0.52

Source: <sup>1</sup>Knight (1980); <sup>2</sup>Prince & Johnson (1982); <sup>3</sup>Walker (1988b)

A number of the trials evaluated the effect on yield of a foliar boron application in early spring; foliar application has been shown to be more effective when applied from stem extension onwards and especially at the start of flowering (Zajonc *et al.*, 1985; Bruchlos & Beyme, 1990). The accuracy with which current analytical methods are able to measure available boron levels in soil needs further evaluation since soil boron concentrations have been shown to double in the space of one month (Knight, 1980; 1981). This fluctuation can be a problem in diagnosing boron deficiency in soil.

#### 7.2.4 Diagnosis and Treatment

The experimental evidence both in mainland Europe and the U.K. clearly shows that yield responses to applied boron may be obtained on soils with less than 0.5 mg/l available boron, depending on the season. On sandy soils, available soil boron levels may need to be as low as 0.3 mg/l before yield response will occur (Shorrocks, 1991). Whilst a positive yield response cannot be guaranteed, the potential yield penalty from not applying boron fertiliser is sufficiently large to warrant treatment. Soil analysis therefore remains the best method of predicting a boron deficiency, although leaf analysis can also be helpful where the crop is already established. No strong relationship between soil and plant boron concentrations was found in a survey of eighty four crops of oilseed rape in 1980 (Johnson, 1980) but such relationships have been demonstrated for other crops elsewhere (Wear & Patterson, 1962).

Experiments in Germany have indicated that boron concentrations in newly expanded leaves from stem extension stage up to fourteen days before flowering need to be 30-35 mg/kg for 90% of maximum yield (Gerath et al., 1975). In France, leaf boron levels above 20-25 mg/kg at stem extension stage are considered adequate (A. Merrien, pers. comm.) although leaf boron concentrations lower than this have been regularly found in crops yielding 3 t/ha with no visible symptoms (Withers, 1988; Glinski et al., 1973; Szukalski et al., 1973). Boron concentrations in the leaves can vary substantially during the growing season but boron usually becomes most concentrated in the flowering organs (Anon, 1981; Glinski et al., 1973). Leaf sampling position on the crop seems critical in view of the immobility of boron in the plant, especially where soil boron supply is low. Leaf boron concentrations in tissue showing deficiency symptoms are less than 15 mg/kg for a range of crops more susceptible to boron deficiency than oilseed rape (Archer, 1985; Gupta et al., 1985). In Scotland, a very close relationship between soil and crop boron concentrations ( $r^2 = 0.61$ ) was found before, but not after, the application of N (A.H. Sinclair, pers. comm.). This was attributed to the acidifying effect of the ammonium sulphate

fertiliser, releasing soil boron for plant uptake. Before N application, an available boron level of 0.5 mg/l correlated with a plant boron concentration of 14 mg/kg.

A number of experiments have investigated the amount and timing of boron fertiliser application for maximum yield response. A rate of only 0.7 kg B/ha, applied as sodium borate to the soil, gave maximum yield in a Swedish experiment (quoted by Holmes, 1980) but applications of 1-2 kg B/ha applied to the soil (Gerath et al., 1975) or 0.4-0.7 kg B/ha, applied as a liquid to the leaf (Bruchlos & Beyme, 1990), have been shown to be required for maximum response. Pot experiments with spring oilseed rape showed that foliar applications of liquid boron must be applied at the start of flowering for maximum yield increase to occur (Zajonc et al., 1985). In these experiments, boron applied to the soil at sowing gave the same increase in yield (15%) as foliar applications but required five times more fertiliser. Early experiments in Germany (Gerath et al., 1975) also indicated that a foliar application of boron (as Borax) could be effective when applied shortly before flowering.

Spring applications of boron to the soil have been found to be more effective than autumn applications of boron (Gerath et al., 1975; Walker, 1988b), presumably because of the susceptibility of boron to leaching. Soil applications of boron should be applied as early as possible in the spring for maximum benefit (Walker, 1988b) although foliar boron applications appear to be a more effective means of controlling a severe deficiency (Kanno, 1967). Current ADAS recommendations are to apply 1 kg B/ha as a soil or foliar dressing in early spring, or to use a boronated fertiliser.

Oilseed rape appears to be relatively tolerant of higher application rates (3-4 kg/ha) of boron to the soil but over-application can be toxic to the subsequent crop (Kanno, 1967). Applications of 2-4 kg B/ha have been shown by Sillanpaa (reported by Shorrocks, 1991) to have some residual effect in the soil for up to 2 years.

The extent to which double low varieties are more susceptible to boron deficiency is unclear. Double low varieties were found to have a 50% lower boron concentration in the vegetative tissue than single low varieties (Schnug, 1987a) but it is not known whether this is simply a reflection of a lower boron requirement. Similarly there is very little data on the effect of boron fertilisation on seed quality, especially glucosinolate concentrations. In Canada, poor seed set in double low varieties is attributed to S, rather than boron, deficiency. However boron, when applied in combination with S, enhanced yield compared to S fertilisation alone, but had no consistent or significant effect on seed glucosinolate content (Nuttall et al., 1987).

In China, where deficiency is severe enough to give crop symptoms, double low varieties are reported to be more responsive to boron fertilisation than single low varieties (V. Shorrocks, pers. comm.).

Experiments to-date also indicate that at N application rates of about 200 kg/ha, boron fertilisation has no or only small positive effects on seed oil concentration, even where positive yield responses are obtained (Gerath et al., 1975; Prince & Johnson, 1982; Withers, 1988).

### 7.3 Manganese

Manganese deficiency is the most common trace element problem in U.K. agriculture and regularly affects susceptible crops grown on sand, peaty or organic soils of high pH. However the deficiency is not commonly found in oilseed rape and field experimentation in both the U.K. and France has failed to show any yield response to foliar manganese applications, even on sites where the deficiency regularly occurs in cereals (A. Merrien, pers. comm.; Withers, 1988).

#### 7.3.1 Crop Requirement

Manganese is required for photosynthesis and is both a constituent and activator of enzymes involved in protein synthesis and lipid

metabolism. A shortage of manganese often results in impaired activity of the nitrate-reductase enzyme with consequent accumulation of nitrate in plant tissue.

Up to 2 kg/ha manganese may be taken up by an oilseed rape crop (Merrien *et al.*, 1988) although uptake varies enormously between crops depending on the soil pH. Data for U.K. crops shows plant manganese concentrations decreasing significantly with increasing pH (Sinclair, 1985). Removal of manganese in the seed is about 100-150 g/ha for a crop taking up 300-400 g/ha of manganese in total, for a yield of 3 t/ha (Szukalski *et al.*, 1973). The highest concentration of manganese is found in the leaves during the vegetative period of growth but it is not until the start of flowering that the greatest uptake of manganese occurs (Zajonc & Borchmann, 1983). A satisfactory manganese supply to developing pods is considered especially important at this time for maximum expression of oil content.

### 7.3.2 Deficiency

Leached sand and podzolic soils are particularly low in manganese but in most other soils manganese is relatively abundant. However availability is greatly reduced by high soil pH and organic matter content. The higher the organic matter content, the lower the soil pH needs to be to prevent deficiency occurring. A temporary shortage of manganese is also often induced under poor soil physical conditions, especially after periods of cold, dry weather which put a poorly rooted crop under stress. Manganese availability has been shown to increase where acidifying fertilisers, such as ammonium sulphate, have been applied (Finck, 1981) although this affect has not been demonstrated for oilseed rape.

Symptoms of manganese deficiency have been recorded in U.K. oilseed rape crops grown on peaty or sand soils of high pH but usually only where the crop is under severe stress, for example in prolonged dry weather or where the crop has been drilled very late. Symptoms can occur at an early stage in growth, especially on peaty soils, and the

oldest leaves are often the most affected (Archer, 1985). Symptoms appear as a fine interveinal chlorotic mottling or yellowing which is especially pronounced along leaf margins. Deficiency is associated with plant manganese concentrations below 20 ppm and can be quickly corrected with a foliar application of manganese, such applications are not however recommended routinely.

### 7.3.3 Yield Response

A number of experiments in Germany (reviewed by Kudryashov, 1986) have shown consistent increases in both seed yield and oil content from the application of manganese to oilseed rape grown on sandy soils. Average yield increases of 0.46 t/ha (12%) in eighteen field trials were reported by Zajonc & Borchmann (1983), with the greatest yield increases occurring in dry years. Pot experiments have demonstrated that yield increases as large as 22% from manganese fertilisation as the result of both increased numbers of pods and increased numbers of seeds per pod. Application of manganese fertiliser before green bud stage or after the start of flowering failed to give the substantial yield obtained in these pot experiments (Zajonc & Borchmann, 1983), emphasizing the need for manganese during the reproductive stages of development.

In the U.K., foliar application of EDTA-manganese in early spring gave no significant increase in yield at fourteen sites between 1985 and 1988 (Withers, 1988). No deficiency symptoms were observed in these trials, even on sites where manganese deficiency regularly occurs in cereals. Leaf analysis confirmed that crops had an adequate manganese content (above 30 mg/kg). Similar observations were noted in Canadian pot experiments in which yield response on an organic soil to manganese fertilisation was obtained in spring wheat but not in canola oilseed rape (Karamanos et al., 1989). Recent field experiments in France have also shown a lack of yield response to manganese fertilisation on fields with high soil pH where a response might have been expected (A. Merrien, pers. comm.).



Although the lack of yield response may be explained by incorrect timing of manganese applications it is more likely that oilseed rape is less susceptible to manganese deficiency than other arable crops. However lack of deficiency symptoms does not necessarily mean the crop is adequately supplied with manganese, especially since the greatest requirement for manganese is during pod development when the majority of leaves have fallen (Zajonc & Borchmann, 1983).

The extensive experiments carried out in Germany have shown that manganese fertilisation has a particularly beneficial effect on oil concentration in the seed (Kudryashov, 1986). Foliar manganese application had no significant effect on oil concentration in U.K. trials but then no yield response was obtained. There is very little information regarding the effect of manganese fertilisation on seed glucosinolate concentration, although at one site in Kent in 1988 glucosinolate content was significantly increased from 28 to 41 umoles/gram by a spring application of manganese (Withers, 1988).

#### **7.4 Molybdenum**

Molybdenum deficiency is a well recognised problem in vegetable brassica crops grown on soils which have not been adequately limed. Although molybdenum deficiency has not so far been identified in oilseed rape grown in the U.K., there is currently much interest in the need for molybdenum.

##### **7.4.1 Crop Requirement**

Molybdenum is an essential constituent of the enzyme nitrate reductase, responsible for the utilisation of nitrate-nitrogen within the plant. This is the most important function of molybdenum and for this reason the molybdenum requirement of crops fertilised solely with nitrate is larger. Molybdenum is also important in other plant enzymatic processes, most notably as part of the nitrogenase enzyme involved in N fixation by leguminous crops.

Crop uptake of molybdenum has been shown to be 15-18 g/ha (Merrien *et al.*, 1988) although values of 2-8 g/ha are quoted by Szukalski *et al.*, (1973). As such, molybdenum is taken up in much smaller quantities than other trace elements. Uptake of molybdenum is known to be limited by applications of sulphate to the soil and in some oilseed rape crops this has been shown to alleviate copper deficiency induced by the antagonistic effect of a high soil molybdenum supply (Karamanos *et al.*, 1989). However on acid soils with low molybdenum supply, applying S fertiliser to correct S deficiency may induce molybdenum deficiency.

#### 7.4.2 Deficiency

Since molybdenum is so important in N metabolism, a shortage of molybdenum produces symptoms of nitrate accumulation; leaves turn a grey/blue-green colour, curl upwards at the edges and often develop marginal necrosis. Leaf laminae may grow perpendicular to, or become misaligned with, the leaf midrib (a process called enation) and the whole leaf blade appears narrowed and distorted, symptoms which are known as 'whiptail'. The growing point may die.

Symptoms of molybdenum deficiency have been recorded in a small number of field crops in France particularly when weather conditions are cold and wet (A. Merrien, *pers. comm.*). Deficiency symptoms are rare in field crops in Germany but plant molybdenum concentrations are considered to be yield limiting in a small number of crops (Schnug *et al.*, 1990).

Molybdenum deficiency has not been reported in oilseed rape in the U.K. where fields in arable rotation are maintained at pH 6.5. Deficiency is associated with acid sandy soils since, unlike other trace elements, molybdenum is strongly absorbed at soil pHs below 5.5. At higher pH values, molybdenum is released into the soil solution and more readily taken up by plants. The dominant effect of pH on molybdenum availability in the soil is well illustrated by survey work in Northern Germany where soil pH accounted for 73% of

the variation in plant molybdenum concentrations of double low varieties (Schnug et al., 1990).

Soil molybdenum content alone is therefore of limited value in predicting molybdenum availability in the soil although a concentration of less than 0.1 mg/kg (extracted with ammonium oxalate) is considered likely to cause a deficiency (Archer, 1985). Available concentrations of soil molybdenum are however normally very low in soils and interpretation of results can be affected by analytical accuracy.

In Germany both soil pH and available molybdenum content are used to diagnose deficiency by means of an Index defined as  $[pH + (10 \times \text{mg Mo/kg soil})]$ . The heavier textured the soil and the lower its pH value, the greater the soil molybdenum content necessary to prevent a deficiency.

A plant molybdenum concentration of 0.5 mg/kg at stem extension stage is considered necessary for optimum growth and concentrations below 0.3 mg/kg are thought to be necessary for yield response to occur (Schnug et al., 1990).

#### 7.4.3 Yield Response

Early experiments in Northern Germany (reviewed by Kudryashov, 1986) on sandy and loamy soils showed that 1 kg Mo/ha applied either as molybdenised superphosphate (0.2% Mo) or as ammonium molybdate (54% Mo) increased seed yield on average by 0.26 t/ha, although responses as large as 0.47 t/ha (21%) were obtained. More recently, yield responses in double low varieties of 0.2 to 0.35 t/ha were obtained from a range of molybdenum fertiliser applications (Schroder & Falke, 1990) on soils moderately susceptible to the deficiency, as identified by the Index method.

Foliar applications of 0.3-0.5 kg Mo/ha during flowering as ammonium molybdate were generally most effective, especially when applied in conjunction with boron, although seed dressings (supplying

0.03 kg Mo/ha) were also effective. In Germany, seed treatment has proved an economic and suitable means of meeting the demands of the oilseed rape crop for molybdenum throughout the vegetative period of growth (Podlesak & Kranse, 1987). Experiments carried out between 1983 and 1985 showed that seed treatment with 7.5 g Mo/ha was as effective as 1 kg Mo/ha applied to the soil. The effectiveness of seed dressings (as low as 5 g Mo/ha) in increasing plant molybdenum concentration has also been demonstrated by Schnug et al. (1990).

In all these experiments, molybdenum fertilisation did not affect the oil content in the seed.

In the U.K., there was no yield response to 0.5% sodium molybdate solution (applied to run-off) at fourteen sites between 1985 and 1988 (Withers, 1988) although, according to the German Index system, these sites were well supplied with molybdenum mainly because of adequate soil pH. Yield responses have been reported in U.K. commercial trials by Phosyn Chemicals Ltd. Again, no yield responses to molybdenum fertiliser applied in spring were found in experiments in France between 1986 and 1988 (A. Merrien, pers. comm). There are unlikely to be situations in the U.K. where the pH of arable soils would normally be left sufficiently acid for molybdenum deficiency to become a problem. Liming is clearly the most effective means of preventing deficiency on acid soils with a pH rise of 0.5 units equivalent to raising plant molybdenum concentration by 0.74 mg/kg (Schnug et al., 1990). Where deficiency is diagnosed in a growing crop, foliar application to supply 30-50 g Mo/ha is recommended (A. Merrien, pers. comm.; Schnug et al., 1990).

## 7.5 Copper

Copper deficiency in the U.K. primarily occurs in cereals and to a lesser extent in brassica vegetable crops but this deficiency has not been recorded in oilseed rape.

### 7.5.1 Crop Requirement

Copper is a constituent of enzymes involved in photosynthesis, carbohydrate and N metabolism and deficiency results in accumulation of phenols and carbohydrate (Mengel & Kirkby, 1987). The uptake of copper is low and typically 30-35 g/ha (Szukalski et al., 1973; Merrien et al., 1988), about a third of this requirement is removed in the seed at a crop yield of 3 t/ha. As with many other crops, copper concentrations in oilseed rape vary little, either between different parts of the plant or during the growing season. For this reason, plant analysis is often of limited value in the diagnosis of copper deficiency.

### 7.5.2 Deficiency

Deficiency in susceptible crops is most likely to occur on sand and chalk soils high in organic matter. Copper is complexed strongly with organic matter and deficiency is common on peaty soils. Copper uptake by the plant is limited by high rates of N and P fertilisers or where other nutrients such as zinc, manganese and molybdenum, are present at a high concentration in the soil solution. In Canada, copper deficiency in canola oilseed rape has been induced by high manganese to copper ratios and by high molybdenum concentrations in the soil, although deficiency was assessed in terms of yield response to copper fertilisation rather than the presence of deficiency symptoms (Karamanos et al., 1989). Where deficiency is severe, susceptible crops show deficiency symptoms in the youngest leaves but often symptoms do not occur until flowering when the plant requires copper for satisfactory pollination.

### 7.5.3 Yield Response

In recent U.K. trials there was no significant yield response in oilseed rape to a foliar application of copper oxychloride (supplying 1 kg Cu/ha) at fourteen sites (Withers, 1988). At one site, the available soil copper level was well below the deficiency threshold of 1.0 mg Cu/l for arable crops (MAFF, 1976).

Large and significant yield responses of up to 50% to soil applied copper have been obtained in Canada on stony, sandy glaciofluvial soils with less than 0.4 mg Cu/l (extracted with DTPA) in the soil (Kruger et al., 1985). Further field experiments on these soils indicated a very strong relationship between canola oilseed rape yield and soil copper concentration, with a threshold concentration of soil copper of 0.35 mg/l being required to ensure 90% of maximum yield (Karamanos et al., 1986). The extractant DTPA is not used in the U.K. for measuring available soil copper but this threshold concentration is equivalent to about 0.7 EDTA-extractable copper in U.K. soils.

These experiments showed that soil applied copper sulphate (5 kg Cu/ha) or chelated copper-sulfonate (0.5 kg Cu/ha) were the most effective forms of fertiliser copper. The chelated copper-sulfonate was just as effective as the copper sulphate in the first year of application but gave no residual value in the second year. Soil applications of granular copper oxide (5 kg Cu/ha) were too slow acting in the first year of application but alleviated copper deficiency in the second year. Foliar applications of copper sulphate or chelate (both supplying 0.25 kg Cu/ha) gave inconsistent results.

The application of a copper fertiliser to an organic soil in pots significantly increased yield of canola oilseed rape in Canada but only where sulphur was not applied (Karamanos et al., 1989). This experiment showed that the applied sulphur alleviated the copper deficiency by limiting the uptake of molybdenum which is well known to be antagonistic to copper uptake.

There is no information on the effect of copper fertilisation on seed quality.

## 7.6 Zinc

On a worldwide scale, zinc deficiency is one of the commonest micro-nutrient deficiencies, especially in maize, leguminous crops

and top fruit. However oilseed rape is not considered a susceptible crop to this deficiency and there have been no recorded cases of zinc deficiency in oilseed rape in the U.K.

#### 7.6.1 Crop Requirement

Zinc is required by plants as an activator of enzyme-driven reactions involved in the synthesis of protein and growth promoting hormones (auxins) and in this respect is similar to the biochemical functions of manganese and magnesium.

The uptake of zinc in the plant at the end of flowering has been estimated at about 500 g/ha of which up to half is removed in the seed (A. Merrien, pers. comm.). However crop uptake of zinc is known to vary considerably depending on soil pH (Sinclair, 1985) and seed offtake values of 80-90 g/ha are more typical for a crop yield of 3 t/ha on a soil with pH 6.0 (Szukalski et al., 1973; Sinclair, 1985).

#### 7.6.2 Deficiency

The zinc content of sandy soils derived from igneous rocks is low but even in soils well supplied with zinc, availability is significantly limited by high soil pH, free calcium carbonate and high concentrations of soil P. Complexation of zinc with soluble organic compounds in soil is thought to increase the availability of zinc to plants where such compounds are in plentiful supply.

The concentration in soil solution is typically very low and once in the plant, zinc is largely immobilised in older leaves. Oilseed rape can tolerate relatively high zinc concentrations in soils because of this general poor mobility of zinc within the plant. For example the winter variety Jet Neuf grew very satisfactorily up to a total zinc concentration in the soil of 300 mg/kg, with only small increases in the zinc content of the seed (Richter et al., 1986).

There is no information on the effect of zinc fertilisation or of high soil zinc supply on seed quality.

## 7.7 Iron

Of all the trace elements, iron is taken up in the greatest amounts (Holmes, 1980; Sinclair, 1985) but deficiency of iron in oilseed rape is unknown. Whilst soils are normally well supplied with iron, plant uptake of this element is severely limited at high pH although, like zinc, iron has the ability to combine with soluble organic compounds to facilitate plant uptake. Iron has a number of important roles in plant respiration, chlorophyll synthesis and in photosynthesis. A 3 t/ha crop removes about 200 g Fe/ha in the rapeseed. Experiments in France indicated that in 20% of oilseed rape crops, yield may be limited by a sub-clinical deficiency of iron (A. Merrien, pers. comm.) but there is no U.K. or other literature to support this suggestion.

## 7.8 Conclusions

1. Oilseed rape does not exhibit trace element deficiencies to the same degree as other crops, for example boron deficiency in other brassica crops or manganese and copper deficiencies in cereals.
2. Oilseed rape has a large requirement for boron and boron deficiency is potentially the most yield limiting trace element under U.K. conditions. However yield responses to boron fertiliser on soils with a small boron supply are very erratic and cannot be satisfactorily predicted at the present time.
3. Symptoms of internal browning, stem base swelling and stem cracking commonly seen in a number of crops in dry seasons have been shown to be reduced by application of boron but are not necessarily indicative of a deficiency.
4. Manganese deficiency may occur in some seasons on leached sands, organic or peaty soils but its widespread use on U.K. oilseed rape crops does not appear to be justified.



Table 25

Trace element deficiencies: symptoms, diagnosis and recommended treatment

Trace Element	Susceptible Soil Types	Symptoms	Leaf Analysis mg/kg	Soil Analysis mg/l	Treatment
Boron	Sands with soil pH over 6.5.  Induced by prolonged dry weather.	Field symptoms rare but can include stunting, restricted flowering and seedless pods. Stem base swelling, stem cracking and necrotic, brittle, lower leaves are also present.	<15	<0.5 (hot water extractable)	a) Use a boronated fertiliser. b) 10 kg/ha Solubor (20% B) applied to the seedbed in 500 l/ha water. c) 5-10 kg/ha Solubor applied to the crop in spring.
Manganese	Sand and peaty soils with soil pH over 6.5. Often associated with poor rooting and cold weather.	Fine interveinal chlorotic mottling on middle and lower leaves, especially pronounced along leaf margins.	<20	Soil analysis unreliable	9 kg/ha manganese sulphate (27-32% Mn) in at least 250 l of water plus wetter when symptoms appear.
Molybdenum	Sand soils with soil pH less than 5.5. Deficiency can occur on heavier soils where soil pH is very low.	Irregular narrowing of leaf blade, thickening of midrib, gives 'whiptail' appearance.	<0.1	<0.1 Tamm's (oxalate-extractable) but soil pH move reliable	0.05% solution of sodium or ammonium molybdate applied to run-off when symptoms appear.
Copper	Peaty soils and sand/chalk soils with over 6% organic matter.	No symptoms recorded.	Leaf analysis unreliable	<1.0 (EDTA - extractable)	2 kg/ha copper oxychloride (50% Cu) in 500 l water at late rosette stage where deficiency confirmed.

There have been no reported cases of zinc or iron deficiency in oilseed rape.

## 8. RECOMMENDATIONS FOR FURTHER STUDY

### 8.1 Nitrogen

Nitrogen rate has a major effect on crop growth and yield, timing of spring application is less critical. More information will be needed on the physiological basis for yield and the interactive effects of sowing date and N application on crop structure, N assimilation within the plant and final components of yield for new shorter varieties, also for semi-dwarf types which may be grown commercially in the future as a result of current developments in breeding.

Efficiency of N recovery by crops is also an important factor which has rarely been accurately measured in previous, largely empirical experiments on N requirement. Autumn N sometimes gives unique, economic yield responses partly at least associated with incorporation of stubble on straw from the preceding cereal crop. There are however conflicting data on the effect of sowing date in particular on the likelihood of response and factors contributing to yield responses from autumn N application are at present poorly understood.

Further R & D is needed to:

- a) Examine the combined effects of sowing and subsequent emergence date, autumn and spring N use on subsequent growth patterns, resultant dry matter production and seed yield for new varieties with shorter growth and more determinate flowering.
- b) Measure in a wider range of situations the efficiency of crop recovery of applied N, influence of crop rooting depth, and the amount of N residues left by the crop, to enable development of an N balance model for assessing crop N requirement. These studies would be coupled with the more intensive investigations already outlined.
- c) Identify further factor(s) which may reliably predict the chances of unique yield responses to autumn N use.

- d) Define the start of stem extension more precisely in terms of physiological stage of development, to improve the basis for spring timing of N (equivalent to apical timing in winter wheat).

To investigate these topics, intensive site studies should be undertaken on soil N and moisture supply, crop growth and N uptake according to the effect of sowing date, autumn and spring N level combinations on crop development. Use of labelled <sup>15</sup>N to study N cycling, in particular the fate of N from crop residues, should also be included at one such intensively monitored site. Less intensive monitoring across a wider range of sites incorporating the same core treatments as at intensive sites would then provide further data for constructing an N balance model and for an assessment of methods to improve the efficiency of N use.

Priority: High

## 8.2 Sulphur

Sulphur is a major component of glucosinolates and, in areas of low atmospheric S deposition, plant S supply has been shown to have a major but variable influence on seed glucosinolate concentration and/or yield. Atmospheric S levels continue to decline and it is expected that the effects of S deficiency in reducing yield of oilseed rape will become more widespread. Further studies are therefore required to:

- a) Identify the extent to which U.K. oilseed rape crops are becoming deficient in S and the critical concentration of plant S below which a yield response can be expected under U.K. conditions.
- b) Investigate whether the proposed link between leaf S status and final glucosinolate content in the seed at harvest could form the basis of a prediction system across sites.

- c) Study the retention and availability of S in soils and the extent to which soil type accounts for variation in seed plant S and glucosinolate content.
- d) Compare alternative strategies of improving the S status of deficient crops and forecasting the need for S fertiliser. This should include establishing the recovery of applied S within the plant and any potential residual value of the fertiliser.

Appropriate studies should take the form of firstly a stratified survey of the S status of U.K. crops and relate seed glucosinolate content to site, soil, seasonal and crop factors. Soil S status and availability for plant uptake during the growing season could be investigated at established sites which are already investigating N x S interactions within the plant.

Priority: High

A conceptual model of the behaviour of S in soil should be developed, also the recovery of fertiliser S applied at different times, rates and forms in plant and soil (possibly using labelled S) would be evaluated in respect of both yield and quality.

Priority: Medium

### 8.3 Trace Elements

There are very limited data on the trace element status of double low varieties of oilseed rape grown in the U.K. but deficiency symptoms rarely occur except in extreme, atypical circumstances. Boron deficiency is reported to occur more widely but field trials rarely detect any yield response to boron fertiliser. European data highlight the importance of boron, manganese and molybdenum in the nutrition of the oilseed rape crop but there are limited data on the extent to which U.K. crops have sufficient levels of these and other trace elements.

Further R & D work is therefore required to establish the extent to which the trace element content of double low varieties in the U.K. is sufficient for growth on a range of soil types, concentrating on those soils with a low supply of trace elements. Guidelines on uptake and offtake of trace elements (B, Mn, Mo, Zn, Cu, Mg) under U.K. conditions are required.

Priority: Low

Further work is also needed to develop a more precise mechanism for predicting boron deficiency in oilseed rape.

Priority: Low

#### **8.4 Crop Physiology**

A more comprehensive review of oilseed rape physiology is needed to identify the extent of existing knowledge, possible interactions with other nutritional requirements and also to enable the development of physiological model(s) to account for observed nutritional effects on crop growth and for seed quality.

Priority: Low

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