CROP RESPONSES TO NITROGEN FERTILIZER AND THE EFFECTS ON LEACHING

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Abstract

The pursuit of high yields by many farming practices to satisfy economic returns and provide food or raw materials for industry has been achieved by deliberate selection of crops and the use of nitrogen fertilizer. Increasingly there have been calls for the optimal use of nitrogen, arising from concerns over nitrate pollution and the costs of fertilizer production. This research programme investigated the comparative yield performance of five crops wheat, barley, lupin, rape and a ryegrass/clover mixture in response to N fertilizer application and the effects of selected crops on nitrate leaching.

A series of field trials over two successive cropping seasons (1989 - 1991) showed that the yield responses of the five crops differed markedly amongst themselves and between seasons although all could be described by a generic, inverse quadratic polynomial model. The highest yielding grain crop was wheat (6.73 t/ha) and the lowest lupin and rape (2.70 and 2.08 t/ha respectively), barley being intermediate (3.73 t/ha). The ryegrass/clover mixture yielded 11.92 t/ha of dry matter on average.

Nitrogen requirements to achieve maximum yields varied according to crop with high N demands being made by wheat, rape and the ryegrass/clover mixture (> 200 kg N/ha). Barley was intermediate in demand with lupin showing a slight yield increase with added nitrogen. The occurrence of a severe drought in 1990 - 91 caused substantial changes in individual crop response to N application.

A detailed growth analysis of four crops was conducted to investigate patterns of dry matter and nitrogen accumulation. Rape and wheat accumulated 80% and 90% of final dry matter yield after 80 days of growth and both crops exhibited a peak nitrogen content at this time, with lowered N contents occurring at the final harvest. Lupin and the ryegrass/clover mixture accumulated dry matter and nitrogen continuously with plant age. Over the four crops on an area basis, the ryegrass/clover mixture exhibited the highest nitrogen in biomass (with mean biomass nitrogen content (NC) of 1.9%) followed in rank order by lupin (NC 2.69%), rape (NC 1.1%) and wheat (NC 1.2%).

During the course of the field trials, a programme of monitoring nitrate in leachate was conducted using lysimeters. Leaching mainly occurred in winter and early spring with high concentrations (> 22.6 mg NO_3-N/l) being observed in October, November and December. The weighted mean nitrate concentration over a period of 2.5 years indicated that the nitrate concentration (18.5 mg NO_3-N/l) from the lysimeters under a ryegrass/clover mixture was significantly lower than that under wheat (20.0 mg NO_3-N/l). Nitrogen fertilizer application was a crucial factor which influenced nitrate concentration in leachate. Applications of N fertilizer to give maximum crop yield in the ryegrass/clover mixture (258 kg N/ha) resulted in a nitrate concentration of 11.5 mg NO_3-N/l in leachate. A corresponding application of 103 kg N/ha to wheat gave a concentration in leachate of 14.8 mg NO_3-N/l. Whilst there was noticeable variation in yield response to nitrogen amongst crops and associated variation in nitrate in leachate, continuous crop cover as provided by the herbage crop was the most effective factor in minimising the nitrate load to groundwater.

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CHAPTER 1 GENERAL INTRODUCTION

1.1 The development of agriculture

In the past 50 years, agriculture, both as a science and technology, has developed rapidly in many aspects, changes being reflected in the technology of crop production, in attempts to maximize yield and more recently in concern for ecological impacts on the environment. Currently the philosophy underlying agricultural development has changed from sole considerations of increasing production *per se*, and associated economic strength that was characteristic of the 1950's, to the concept of 'sustainable agriculture for development' (Woodmansee 1984; McDougall 1990). After many years of the practice of intensive cropping in developed countries and the introduction of the "green revolution" (Brown 1970) to developing countries in the 1960's and 70's, sustainable agriculture emerged as a new idea. Although definitions of the term 'sustainable agriculture' vary, it is widely accepted that this phrase refers to an agricultural production system which has the ability to maintain production in the face of stress or shock (Conway and Barbier 1990).

A stress can be thought of as a phenomenon such as a frequent or continuously increasing event as in soil erosion or nitrate leaching which may cause water pollution and pose a health hazard in an area. A shock on the other hand represents a relatively large and unpredictable force such as a rare drought or a massive increase in prices of raw materials imposed upon the agricultural system. The emergence of the idea of 'sustainability' signalled that agriculture was no longer regarded as an industry solely for the supply of food and feeding stuffs or raw materials for other industry and put an emphasis on long-term stability. The core of the concept rests on a 'global' evaluation of agriculture taking economics, environment impacts and efficient use of resources into account whilst still recognizing the need to increase production and build nation's economies. This goal is paramount under the current international economic order, environment impacts and the high pressure of population growth. This aim, however, is often restricted by the natural limitations of the yielding capacity of crops, and the available farming system.

1.2 Yielding capacity of crops

Yielding capacity may be defined as the yield that a crop may produce on a unit area of land under defined soil and climate conditions. It may be measured either as total biomass produced per unit area (usually measured as above ground biomass) or as economic yield, namely that part of the plant which is harvested for sale and has economic (monetary) value. Crop yield may be affected by many factors, such as soil, climate, diseases, pests, weeds, fertilizers and cultural management for example. Also, different crop species characteristically give different yields. With similar soil type and climate conditions, a wide range of yielding capacity of different crops is quite commonly observed. For example, in Britain potatoes give as twice as high yields as cereal grains (10 as opposed to 5 t dry matter/ha) and grass herbage outyields maize silage (average 10 t dry matter/ha) by a factor of 1.5 (Cooke 1983). The yield (15 t dry matter/ha) of grass herbage may be three fold greater than the grain yield of cereal (Cooke 1983). Similarly, the economic yields and crude protein yields (Table 1.2-1) may vary noticeably.

Table 1.2-1. Yields of major crops in Southern China (Guo 1984, unpublished data from a survey).

Crops	Biomass yield DM t/ha	Economic yield DM t/ha	Protein yield DM t/ha
Wheat + Rice	26.7	13.4	1.5
Wheat + Soybean	16.77	8.7	1.2
Ryegrass/Clover	26.1	26.1	4.1

Economic yields vary due to the differing biological efficiency and the duration of the growth season of crops (Spedding, Walsingham and Hoxey 1981). In some cases, the economic yield of grass herbage may be doubled or even tripled over cereals in terms of dry matter or crude protein yield (Cooke 1983).

In contrast to cereals and herbage crops, the protein-rich seed crops like lupin and oil seed rape usually give low economic yields. For instance, lupin seed yield in the U.S. in 1940's was about 1.1 t/ha on average, with 2.2 t/ha being considered a high yield (U.S. Department of Agriculture 1948). Similar performance was observed in the U.K. in the early 1940's, ranging from 1.5 to 2.3 t/ha (Moore 1944). After many years of agronomic research, breeding of new varieties has raised lupin seed yield to 3.97 t/ha on average and up to as high as 6.56 t/ha (Postiglione 1983).

In oilseed rape production, oilseed yield has increased from 1.95 t/ha from the late 1960's to 2.95 t/ha in 1980 nationwide in the U.K. (Johnson 1981; Munir 1982). Despite lower yielding capacity, the economic value for oil seed has led to considerable interest in new cropping practices in the U.K. (Agriculture and Food Research Council 1987).

On the other hand, as dynamic biological components of arable ecosystems, different crops have different effects on the environment in which they grow, especially on the influence of nitrogen circulation (Sprent 1987). Typical methods of growing cereals, especially ploughing and sowing may cause peak values for soil nitrate which usually oversupplies the emerging crop with nitrogen. As the crop develops, the demand for nitrogen increases and additional N inputs as fertilizer are needed to maintain yield. It is, however, not necessary to supply a legume crop with nitrogen fertilizer for normal growth.

In practice, the high yield of a crop is often achieved by supply of a large quantity of the major plant nutrients namely phosphorus, potassium and nitrogen. Of these, nitrogen is the most important factor both in raising yield (Cooke 1984) and providing the potential to cause environment damage via eutrophication or nitrate contamination to water (Ministry of Agriculture, Fisheries and Food 1974). Nitrogen fertilizer as a plant nutrient can effectively stimulate crop yield in most cases and represents a large proportion of capital investment and consumption of resources in many farming systems. Taking the U.K. in the late 1970's as an example, nitrogen fertilizer used in agriculture consisted of 21.1 - 65% of input energy at the nationwide scale to farm level respectively, and about 6.5 - 11.8% of monetary investment was spent on nitrogen fertilizer alone (Spedding 1983). There is no doubt that nitrogen fertilizer plays a very important role in modern farming practices and efficient utilization depends on an understanding of crop responses to nitrogen fertilizer.

For the control of nitrogen circulation in arable ecosystems, it is fundamentally important to understand the biological effects of the crops which form the basis of a farming system and govern the success of an arable ecosystem as a whole.

1.3 The source of nitrogen as a plant nutrient

Apart from nitrogen reserves (organic matter) in soil and atmospheric nitrogen fixation by legume crops and some free living microorganisms (Postgate 1981), the main source of nitrogen as a plant nutrient falls into two categories: organic manure and inorganic fertilizer. Organic manures have a range of beneficial properties such as improving soil structure, nitrogen and reducing the risk of loss by leaching (Briggs and Courtney 1985; Russell 1982) and, in most mixed farming systems, are effectively free (Guo and Yuan 1987; Arden-Clarke and Hodges 1988). But the substantive change (essentially post 1940's) from use of organic manure to inorganic fertilizer in the U.K. may be explained by the fact that inorganic fertilizers do offer some major advantages over organic manure (Briggs and Courtney 1985). The merits they offer are mainly a clean, easy to handle N source, often associated with higher yields, which are currently considered sustainable.

Because of this, the use of inorganic fertilizer has increased remarkably over the last 50 years and is likely to continue to increase (Cooke 1984). For example, the annual amount of inorganic nitrogen fertilizer usage has grown 16-fold from 1939 to 1980 in the United Kingdom (Hood 1982). In many farming systems the technology for the application of nitrogen fertilizer is a crucial factor concerned with reducing cost (Sylvester-Bradley and George 1987), maximizing and stabilizing yield (Guo and Bradshaw 1992), enhancing economic return (Cooke, 1983), and most important, reducing potential risk on nitrate leaching from arable land (The Royal Society 1983).

The forms of nitrogen available to plants as an inorganic fertilizer are mainly urea ($CO(NH_2)_2$, 45% N), ammonium sulphate ($(NH_4)_2SO_4$, 21% N), calcium nitrate ($Ca(NO_3)_2$, 15.5% N), ammonium nitrate (NH_4NO_3, 34.5% N) and aqueous ammonia (NH_4OH, 21 - 29% N). In the U.K., about two-thirds of N fertilizer currently used is in the form of ammonium nitrate (The Royal Society 1983). Ammonium sulphate is now rarely used in the U.K. probably because this form of fertilizer has an acid base ($SO_4^=$) which may reduce soil pH. Aqueous ammonia is not commonly used in the U.K. but accounted for 35% of total N fertilizer applied to field crops in the United States and 30% in Denmark in the early 1980's (Briggs and Courtney 1985).

1.4 Crop responses to nitrogen fertilizer

The nitrogen demand of crop species differs widely. For cereal and oilseed rape production, supply of nitrogen as fertilizer is usually unavoidable, and the response of the crops to fertilizer is remarkably positive. Conversely a legume crop with its ability to fix atmospheric nitrogen implicitly will require a lower level of soil mineral N with less or no nitrogen fertilizer application. Substantial nitrogen fertilizer applications are also made to temporary and permanent grassland. For example, from the middle of the 1950's to the later 1970's the amount of nitrogen fertilizer applied to grassland in England and Wales increased from about 20 to over 100 kg N/ha (Morrison, Jackson and Sparrow 1980). It has been estimated that towards the early 1980's an annual expenditure of about 180 million pounds sterling was nationally spent on nitrogen fertilizer alone on temporary and permanent grassland (Morrison, Jackson and Sparrow 1980).

The main guide to fertilizer practice in the U.K. is the fertilizer recommendations published by the Ministry of Agriculture, Fisheries and Food. This guide presents the fertilizer requirement for average yielding in the U.K. given a baseline fertilizer level (the soil index) in the soil resulting from previous cropping of the land (Table 1.4-1).

Table 1.4-1. Recommendations of N, P, K (kg/ha) for spring sown (S-S) and autumn sown (A-S) crops (MAFF 1983).

	Soil* Index	Barley S-S	Wheat A-S	Rape S-S	Rape A-S	Field bean S-S	Ryegrass/clover S-S & A-S
N	0	100	120	188	226	nil	100 per cut
P	2	17	17	28	28	17	56
K	1	31	31	104	104	42	156

*Soil index given here is for the experimental site described in Table 1.10-2.

Crop response to nitrogen fertilizer varies according to soil type, climate, methods of application and the optimum levels of nitrogen fertilizer application may vary considerably. For example, the optimum level of N fertilizer for wheat may range from 40 to 150 kg N/ha (Baethgen and Alley 1989; Gospodinov 1986), whilst that of N fertilizer for grass herbage may vary from 260 to 530 kg N/ha (Williams 1980). It is clear that in order to raise yield and hence a good economic return it is essential to understand the response to nitrogen fertilizer under specific soil and climate regimes. For this reason amongst others much research has been carried out to describe the yield-nitrogen relationships.

1.5 Mathematical models to describe crop response to N fertilizer

Many empirical models have been built to evaluate the response of crops to nitrogen fertilizer. Thornley (1978) described three typical response equations to describe crop yield as a function of the level of fertilizer.

The equations are

$$Y = a_0 + a_1X + a_2X^2 \qquad (1)$$

$$\frac{1}{y} = \frac{1}{a} + \frac{b}{aN} \qquad (2)$$

$$\frac{1}{y} = \frac{1}{(1 - N/\alpha)} \left(\frac{1}{A} + \frac{1}{B_n N} + \frac{1}{B_p P} + \frac{1}{B_k K} \right) \quad (3)$$

where y is crop yield (kg/ha);

X is fertilizer level (kg N/ha);

N, P, K are.soil fertilities (kg N, P, K/ha);

a_0, a_1, a_2, a, b, α , A, B_n, B_p, B_k are parameters of the equations accordingly. Equation (1) is a polynomial equation and (2) and (3) are inverse yield equations.

In equations (2) and (3), N, P and K are assumed to be the total available fertilizer summing the initial soil fertility with added fertilizers. Thus, N, P, and K variables are in the forms of

$$N = x + c1 \quad (4)$$

$$P = p1 + c2 \quad (5)$$

$$K = k1 + c3 \quad (6)$$

where x, p1 and k1 are added nitrogen, phosphate and potassium. c1, c2 and c3 are original soil fertilities of nitrogen, phosphate and potassium.

Substituting equations (4), (5) and (6) into equations (2) and (3) gives

$$\frac{1}{y} = \frac{1}{a} + \frac{b}{a(x + c1)} \quad (7)$$

$$\frac{1}{y} = \frac{1}{(1 - (x + c1)/\alpha)} \left(\frac{1}{A} + \frac{1}{B_n(x + c1)} + \frac{1}{B_p(p1 + c2)} + \frac{1}{B_k(k1 + c3)} \right) \quad (8)$$

When the plant nutrients phosphate and potassium are not in short supply, and may be assumed to exceed the level which will not limit crop yield, equation (8) may be simplified to

$$\frac{1}{y} = \frac{1}{[1 - (x + c1)/\alpha]} \left[\frac{1}{A} + \frac{1}{B_n(x + c1)} \right] \quad (9)$$

Another well-established model was described by Sparrow (1979) in comparing five mathematical models all of which may represent the relationship between the dry matter yield of grass herbage and nitrogen fertilizer. After comparison of models using 84 sets of experimental data an inverse quadratic polynomial was considered to be the 'best' model to describe most of the experimental data.

Sparrow's inverse quadratic polynomial model is

$$Y = \frac{b_0 + b_1X}{1 + b_2X + b_3X^2} \quad (10)$$

where Y is dry matter in kg/ha, X is applied nitrogen fertilizer in kg N/ha and b_0, b_1, b_2, b_3 are constants.

Given a description of crop yield in relation to fertilizer N, yield response is defined as dy/dn, where dy is the increase of dry matter yield in kg/ha and dn is the increase of fertilizer applied in kg N/ha. Maximum response (Y_m) is defined at a level of N where

$$dy/dn = 0$$

and the Economic Response (Y_e) is defined as

$$dy/dn = FP/PP$$

where FP is price pound (£) per tonne of fertilizer in form of N and PP is the commodity price, pound (£) per tonne of product (dry matter).

The economic response is the yield at a nitrogen application level which the marginal return is maximized because the cost of fertilizer is not matched by financial return from the increase in crop yield beyond that nitrogen application level.

Y_m and Y_e may be calculated by iteration examining yield increase (kg) to per kg N application, once the yield response curve is known.

In some experiments on grass or foliage reported in the literature, a response variable to N fertilizer known as Y_{10} is used. Y_{10} is defined as

$$dy/dn = 10$$

where dy is the increase of yield (kg/ha) and dn is the increase of N fertilizer (kg N/ha).

The prices used in this thesis for estimation of economic response were the statistical price published at the end of June 1991 in 'Farmer's Weekly' subject to a assumptions over moisture content of products and dry matter yield. A price of 110 pounds per tonne of the fertilizer Nitram (N 34.5%) gives a cost of £318.84 per tonne of N and a price of 125 pounds per tonne of barley (11% standard water content) on the market gives a price of £140.45 per tonne of dry matter grain as does the price of rape seed and dried ryegrass/clover (Table 1.5-1).

Table 1.5-1. Price of farm products and N fertilizer used for estimation of economic response in this thesis.

Item	Moisture % or N %	Price £/t	£/t DM	FP/PP	Date & source
Nitram	34.5% N	110.00	318.84		1
Wheat grain	11%	134.10	150.67	2.12	2
Barley grain	11%	125.00	140.45	2.27	3
Rape seed	9%	215.00	236.26	1.35	4
Broad bean	14%	184.00	213.95	1.49	5
Dried grass	11%	134.35	150.96	2.11	6

1. Jul. 5 1991, Company price, North West of England and Wales.
2. Jul. 5 1991, Farmers Weekly, U. K. average.
3. Jul. 5 1991, Farmers Weekly, U. K. average.
4. Jul. 5 1991, Farmers Weekly, West Midlands.
5. Jun. 14 1991, Farmers Weekly, West Midlands.
6. 1987, Agriculture statistics (MAFF 1988), U.K. average.

The price of lupin seed was not available so the price of broad bean was used as a substitute.

1.6 Nitrogen uptake and the growth pattern of the crops

Although nitrogen utilization by crops is a complex issue and influenced by many interrelated factors, crops are always dominant factors on the nitrogen dynamics in arable ecosystems and tend to have different ecological impacts (Frissel 1978).

It is well established that growth and development of crops are irreversible biological processes. Environmental stress like drought and waterlogging may prohibit or severely reduce the yield of seed-producing crops if the stress occurs at critical growth stages such as germination or flowering (Harper 1983). The pattern of crop growth and associated nitrogen uptake, however, is more likely to be determined by a particular crop than a seasonal function. For example, oil seed rape may reach maximum dry matter production 142 - 179 days after emergence and maximum nitrogen accumulation at the end of flowering, between 120 - 139 days after emergence (Casarini, Haag, Sfredo and Minami 1984). Cereal crops exhibit a similar pattern as oil seed rape in dry matter and nitrogen accumulation (Darroch and Fowler 1990). Wheat has been shown to take up 72 - 84% of the total nitrogen requirement by the time of stem elongation (Pandrangi and Wankhade 1989) and have the highest daily uptake rate in the period immediately after leaf sheaths become erect (Zadoks' growth stage 30) (Baethgen and Alley 1989).

In wheat and oil seed rape production, the rate of nitrogen accumulation was faster than dry matter accumulation before flowering (Darroch and Fowler 1990; Casarini, Haag, Sfredo and Minami 1984). Contrastingly lupin accumulates nitrogen in plant tissues coinciding with plant development (Duthion, Amarger and Mariotti 1987).

Unlike oil seed rape, wheat and lupin, which usually translocate vegetatively accumulated nitrogen to reproductive parts at the seed development stage, ryegrass/clover mixtures under cutting remain in the vegetative growth stage because of continuous truncation of inflorescence development. In consequence they accumulate nitrogen on a proportional basis to dry matter production that in turn is largely influenced by seasonal temperature and water supply (Osbourn 1980).

For a better understanding of the performance of crops and their ecological impacts it is essential to examine the growth patterns of the crops and their manner of utilizing nitrogen. Furthermore, the most important ecological impact of N fertilizer application probably is nitrate leaching from arable land under intensive cropping.

1.7 Effect of crop and N fertilizer application on nitrate leaching

Nitrogen leaching may be defined as the transport of nitrogen in water-soluble forms out of the root zone of a soil (White 1987), and naturally, is a part of the nitrogen cycling process within soil-plant systems, or more widely, the biosphere. The process of natural cycling does not cause any problems to human society. However, it is intensified or enforced by the practice of heavy application of nitrogen fertilizer. High concentrations of nitrogen (NH_4-N and NO_3-N) in freshwaters, lakes and groundwater may cause serious damage to environment (The Royal Society 1983), mainly through eutrophication and impose health problems to human society, mostly concerned with methaemoglobinaemia and cancer although little direct evidence has been provided to show a strong and direct link these two diseases with nitrate concentration in water (Select Committee on The European Communities 1989).

In Britain the most nitrate loads to freshwaters, lakes and groundwater derive from agricultural land. It has been estimated that about two-thirds of inputs of nitrogen to these water sources come from agricultural land in the U.K. in 1978 (The Royal Society 1983) and sometimes the nitrate load to water could rise to as much as 85% from agricultural sources (Holden 1976). It has also been calculated that about 12% of total nitrogen input to agricultural land (including inputs from rainfall and biological nitrogen fixation) or 28% of chemical fertilizer alone may be leached out of the soil root zone in the U.K. (The Royal Society 1983).

As stated in the previous section, the key factor to enable minimization of the potential risk of nitrate leaching may rely on the understanding of crops and cropping associated with soil, climate and the factors related to leaching.

1.8 Research aims

The principal objective of the research reported in this thesis is to critically compare the yield response to nitrogen fertilizer application of differing crops and consider the effects on soil nitrogen content and potential risk on nitrate leaching. Whilst there is considerable information on the yield responses of individual crops to nitrogen comparative assessments of differing crops at the same site under similar climatic conditions are rare. Two cereal crops (barley and wheat), a legume crop (lupin), oilseed rape and a ryegrass/clover mixture for a given soil type over two seasons were compared. These were chosen since they were key components of farming systems, and so that the results could have a practical value of wide range. Moreover the different biological characteristics of the selected crops might be expected to illustrate differences in response to nitrogen fertilizer both in pattern of biomass accumulation and production of economic yield.

1.9 Crcp review

Barley

Barley (*Hordeum vulgare* L.) is a major cereal crop forming a main stay in cereal production systems in the world and U.K.. The species shows wide adaptability to soils and climates (Spedding 1983). Spring barley provides an alternative cereal for farmers in crop rotation especially when circumstances prohibit winter wheat or winter barley. The growing season (from early March to early July) of spring barley is shorter than that of wheat so that land becomes available earlier for succeeding crops in comparison to winter sown cereals. Its short total growth period, typically 120 days, and fast rate of vegetative growth demands a high supply of nitrogen (80 - 120 kg N/ha, MAFF 1983) at an early growth stage (before Feekes' growth stage 2 in a total 11.1 growth stage classification system, Tottman and Makepeace 1979), typically half being applied into the seedbed and half applied during vegetative growth at late April or early May (ADAS and MAFF 1975). This demand characteristic for N fertilizer has the potential to lead to nitrate leaching, if associated with high precipitation on light soils.

Barley yields in the U.K. typically range from 3.2 t/ha to 4.5 t/ha (ADAS 1975). Low rainfall may considerably reduce yield, especially if soil water is limiting in March, April and June. The N fertilizer for barley is usually applied in the range from 20 to 120 kg N/ha according to the soil index, soil type and climate.

Wheat

In most agricultural regions of the world, the acreage under wheat (*Triticum aestivum* L.) is much larger then that under barley (Spedding 1983) and in the U.K. in 1985 was equivalent to that under barley (MAFF, DAFS and MANI 1986a). Wheat is a main cereal crop in arable production systems throughout the world. Being a national staple in 43 countries (Quisenberry and Reitz 1967), it shows considerable adaptability to climate. For example in north-western Europe, temperate latitudes provide a continuous growing season of 10 to 11 months. In contrast, in parts of the U.S. and the northern areas of North America, cold winters dictate that wheat is sown in spring, giving a cropping season as short as three months, while in lower latitudes the season is limited by high temperature and drought and is typically of six months duration (Austin 1986).

Wheat yields have been successively increased over the last fifty years, and may increase in the near future (Evans and Peacock 1981). In 1979 the percentage of land under wheat was about 31.4% of the total land under cereal crops, and 18% of the total arable land worldwide (Spedding 1983). Although the acreage under wheat changes slightly from year to year, total wheat grain production has increased primarily due to enhanced yield per unit area. There were 233 million hectares under wheat in 1965 (Quisenberry and Reitz 1967) and 239 million hectares in 1979 (Spedding 1983) worldwide, (a 2.6% increase in acreage over that period). The total wheat grain production, however, rose from 267.95 million tonnes in 1965 to 429.70 million tonnes in 1979, reflecting an increase of 56.5% in yield per ha.

The changing face of wheat production in EEC countries has been a consequence of the economic incentives offered by the EEC Common Agricultural Policy, coupled with the continued availability of fertilizers, herbicides, pesticides and new cultivars. This has stimulated the production of wheat in member states both in terms of the area grown and the yield of grain per hectare. Taking the U.K., wheat cropping area has increased from 0.83 M ha in 1969 to 1.94 M ha in 1984, and the yield per hectare has increased from 3.95 t /ha to 7.07 t /ha in 1984 (MAFF, DAFS and MANI 1973 and 1986b). Similar increases in yield have occurred in France, Germany, Holland and Belgium. The EEC is now a net exporter of wheat and is in competition with lower-cost producers (Austin 1986). Evans and Peacock (1981) summarized the technological background to raising the yield of wheat arguing that it was partly due to increased inputs such as fertilizers, herbicides and pesticides together with improved agronomic practices but also due to the introduction of new cultivars provided through plant breeding.

It seems that the importance of wheat is quite clear since wheat alone provides almost 20% of the total food calorie consumption for the people of the world

(Quisenberry and Reitz 1967), or more than 400 million metric tonnes in a single year (World Food and Agriculture Organization 1978). Moreover calculations have shown that the established potential yield of wheat attainable in England when growing conditions are ideal is about 14 t /ha for varieties currently grown (Cooke 1982). In practice, maximum yields obtained in experiments on favourable soils and in good years are 11 - 12 t /ha. Average yields on a country wide basis were 7.5 t /ha in the climactically favorable year of 1984 and 5 - 6 t/ha on average.

Recommended nitrogen fertilizer applications range from nil at soil nitrogen index 4 to 140 kg N/ha at soil nitrogen index 0 (MAFF 1983) according to soil type and summer rainfall in the U.K..

Lupin

Lupin (*Lupinus albus* L.) seeds have been a key component of animal feed-stuff and human dietary interest since the 1920's (Sator 1983). The various kinds of lupin products such as lupin soup, lupin steak, lupin oil, lupin fiber and lupin margarine with 20% lupin constituents as well as lupin cheese reflect the very wide variety of culinary uses of lupins in the past (Sator 1983).

Historically the range of cultivation of lupin covers countries from the Iberian Peninsula to the coastal regions of Turkey and the Near East, as well as along the Nile Valley as far south as the Sudan (Williams and Brocklehurst 1983). Lupins have also been grown in America (U.S. Department of Agriculture 1948). In Eastern countries, lupins have been used as a ground cover plant and for soil improvement, being mainly confined to light, poor yielding land (Moore 1944).

Despite the extensive cultivation of lupin worldwide in farming history, lupin cropping has declined substantially in the European Mediterranean countries. Taking Italy for instance, the acreage under lupin had decreased from 46900 hectares in 1950 to 4650 hectares in 1980 (Postiglione 1983). There appear to be several reasons for this.

Firstly, the seed yielding ability of lupins was unstable although the species displayed adaptability to a variety of climatic and soil conditions. The establishment of *Lupinus albus* as a major grain legume is dependent on success in increasing the rate and synchronization of stem and seed development. It has been established that growth rate in the species responds according to genotype, to temperature treatments (vernalisation effects) and to photoperiod during the seedling and pre-flowering stages (Rahman and Gladstones 1972). These responses were, however, highly variable from season to season, making it impossible to predict the optimal sowing date for the promotion of a balanced development of the vegetative and reproductive phases and also to ensure early maturity with a maximum harvest index. Many of these growth characteristics are far from ideal in the shorter seasons that prevail after spring sowing in cooler latitudes (Williams and Brocklehurst 1983).

Secondly, the increasing availability of cheap fertilizers following the end of the second World War made lupins less important as a green manure.

Thirdly, the feed and food value was limited in that some species contained a poisonous alkaloid in all parts of the plant. Great care was necessary in feeding lupin to sheep and not more than a quart pound (113 g) per head per day was recommended as feed intake for ewes and the crop should not be fed to ewes in lamb (Moore 1944).

The situation has changed to some extent however in recent years. Comparative studies have indicated considerable genotypic diversity in lupin and the total number of varieties may extend to several hundred (U.S. Department of Agriculture 1948). Genetic resources have been enriched by collection of species from countries bordering the Mediterranean (Simpson 1983) and the development of biotechnology, particularly protoplasm fusion, has led to 18 different interspecific and intergeneric hybrid plant varieties (Sator 1983).

Other investigations of the pattern of variation among populations of *Lupinus albus* and improvements in agronomic adaptability over a wide geographical range have been successfully carried out by selection (Simpson 1983; Williams and Brocklehurst 1983). The quality of lupin seed has also been improved by selection. A number of alkaloid-free cultivars, Multolupa (*Lupinus albus*) and Type 53 (*Lupinus albus*) for example, are now available and give seed yields as high as 3.97 t/ha on average with the highest yield being 6.56 t/ha (Postiglione 1983).

Due to the increasing need for plant protein for human and animal consumption, lupin as a temperate legume crop may be a good choice for profitable farming. Lupin seeds have a high protein content compared with other temperate legume crops (Table 1.9-1).

Table 1.9-1. Ranges of seed protein and amino acid content (% dry matter) in legume species (from Monti 1983; Sator 1983).

Species	Proteins	Lysine	Methionine	Cystine
Vicia faba	22.0 - 37.0	6.2 - 6.5	0.6 - 1.0	0.6 - 1.7
Pisum sativum	15.5 - 39.7	6.9 - 8.5	0.6 - 1.0	0.8 - 1.7
Lupinus albus	17.0 - 44.9	4.3 - 5.8	0.3 - 0.5	1.0 - 2.5
Lupinus. mutabilis	31.7 - 45.9	5.3	0.4 - 1.4	1.4

Beyond its seed value, lupins may be used in many ways. For light sandy soils and acid soils, lupin may be grown as a soil improver. Their ability to produce an abundance of herbage and seed on sandy, acid soils makes them worthy of consideration as potential forage and break crops for crop rotation. In this way, lupin biomass incorporated into soil may either enlarge the soil-plant nutrient pool via biological nitrogen fixation or retain soil nitrate in organic matter and prevent leaching. The average residual soil nitrogen of a legume crop may be as high as 40 - 80 Kg N/ha (Doyle, Moore and Herridge 1988) and this is obviously a valuable benefit for successive crops. After lupin cropping, the yield increase of a following wheat crop in the absence of nitrogen fertilizer was reported between 0.29 to 1.22 t/ha grain in the first year and as high as 0.39 t/ha grain in the second year in Florida (Doyle, Moore and Herridge 1988). The amount of N_2 fixation by lupin growing in field conditions could be as high as 72 to 228 kg N/ha, which sometimes was more than the amount of nitrogen combined in the dry matter of the lupin crop itself (Herridge and Doyle 1988).

Another lupin species, *Lupins arboreus*, may grow vigorously at very low calcium and phosphate levels and increase the plant and soil nitrogen pools

(Palaniappan, Marrs and Bradshaw 1979). For this reason lupin may be a good species for land reclamation.

Although some varieties of pear lupin (*Lupinus mutabilis*) may be sown in autumn in a cropping programme the alkaloid content is higher than white lupin (*L. albus*) (Agricultural and Food Research Council 1987).

In addition to the advantages of nitrogen fixation and soil improvement, the crude protein yield of lupin is usually about the same level or more than that of barley and oilseed rape on an area basis.

Oilseed rape

Oilseed rape (*Brassica napus* L.) is another important crop in arable ecosystems. Oilseed residue, after oil extraction, is a high protein feed which is increasingly demanded for animal production. In root system, plant nutrient requirement and yielding capacity as well as economic value, oilseed rape differs from the crops previously mentioned. Its well developed root system is similar to lupin but the species lacks the ability to fix aerobic nitrogen.

Oilseed rape is grown widely all over the world and may be sown in spring or autumn in temperate cropping regions. Autumn sown oilseed rape, however, has become more popular than spring sown rape because of higher seed yield which may be harvested almost at the same time as spring cultivars. In the U.K., there has been a rapid increase in area of oilseed rape and its products since 1970. The acreage has steadily increased from 4000 ha in 1970 to 295620 in 1985 (MAFF, DAFS and MANI 1973 and 1986a) and was projected to be about 340000 ha in 1987 (Agricultural and Food Research Council 1987). The acreage devoted to winter varieties of oilseed rape accounted for over 95% of the U.K. rape seed crop in the late 1980's (NIAB 1989). The attraction of this crop to the growers depends heavily on current EEC Common Agricultural Policy: namely guaranteed purchase and price. The increase in the world commodity price for rape is another reason for the rising interesting of growers.

Oilseed rape is, however, not a new crop to the U.K.. From the seventeenth century it provided much of the local demand for vegetable oils and oilseed meals until their replacement by cheap imports from the middle of the nineteenth century (Spedding 1983). In Britain, the season is sufficiently long and the winter is typically mild enough to allow both autumn and spring sown oilseed rape to be grown, especially for more productive autumn sown cultivars such as c.v. Cobra.

The performance of oilseed rape over the last two decades has shown its reliability in creating and sustaining a steady market with a consistent and satisfactory quality in this country. The main arable areas of Britain present no serious climatic limitations for winter oilseed rape. Drought rarely occurs early enough to affect the main growth period of the crop, and although low rainfall can pose establishment problems and high summer rainfall can cause harvesting losses, this is more a function of season than of district.

The crop is adapted to a wide range of soils but shows some susceptibility to water logging partly because of the direct effects of anaerobic conditions and partly because of the importance of spring growth to winter oilseed rape as an early flowering crop. Performance may be reduced if the soil pH is much below 6.0.

Another advantage is that oilseed rape fits well into cereal farming systems because crop production requires almost the same basic equipment as cereals. On some heavier soils in the U.K., rape has replaced sugar beet and potatoes in rotation with winter wheat or winter barley (Spedding 1983).

The seed yield of spring sown oilseed rape in field trials ranges from 1.89 t/ha to 2.18 t/ha with an associated oil content of 41.2% to 43.4% (NIAB 1989) and for autumn sown cultivars in field trials it usually ranges from 3.4 to 3.8 t/ha with the same oil content (%) (NIAB 1989). Yield has steadily increased from 1.95 t/ha in 1969 to 2.94 t/ha in 1980 nationwide in the U.K. (Johnson 1981; MAFF, DAFS and MANI 1973 and 1982).

The response of oilseed rape to nitrogen is remarkably positive and the requirement for nitrogen fertilizer is usually higher than for cereal crops. Autumn sown rape requires more nitrogen fertilizer than spring cultivars. The MAFF recommendation for nitrogen fertilizer ranges from 88 kg/ha to 188 kg/ha for spring sown cultivars and

126 kg N/ha to 226 kg N/ha for autumn sown cultivars at soil nitrogen indices 4 to zero respectively (MAFF 1983).

Ryegrass/clover mixtures

Grassland, providing herbage for grazing or cutting for animal feed stuff, forms a unique farming system in the world, especially in arid or semi-arid regions. Permanent grasslands cover approximately 24% of the world's surface area (Buringh 1985). In 1978, there were 3151 M ha of permanent pasture comprising 69% of the total agricultural land in the world.

In the United Kingdom, 2.3 M ha of temporary pasture in 1976 comprised 12% of the total agricultural land (Spedding 1983). Among the species of grass and leafy legumes, ryegrass (*Lolium perenne* L. and *Lolium multiflorum* L.) and white clover (*Trifolium repens* L.) are very important crops. White clover is a high quality forage legume and can grow well together with ryegrass in mixture. Such mixtures provide an opportunity for farmers to practice temporary grass or ley farming system as an alternation of cereal crops.

Ryegrass and white clover mixtures may be sown in autumn or in spring. Being very winter resistant, autumn sowing of ryegrass/clover mixtures is quite common in the U.K. especially where no serious soil and climatic problems prevent husbandry practices. When the mixture is sown early in autumn it may rapidly establish a ground cover and develop a substantial root system before growth is limited by low winter temperatures. Autumn establishment predisposes the crop towards vigorous vegetative growth early in the next spring which often ensures a high yield and good quality either for grazing or cutting.

Ryegrass/clover mixtures show drought resistance since ryegrass has a very strong proliferating root system. Its high dry matter yield, usually 10 - 14 t/ha, (Spedding 1983) and quality of digestible leaf protein are key agricultural features.

Such mixtures may maintain high production, around 10 t/ha herbage, for 3 or 4 years, and then the land may be turned to cereal or oilseed rape production enabling use of accumulated nitrogen during the years under temporary pasture via gradual mineralization of its organic matter. In temporary pastures kept for more than 3 or 4 years, reseeding is usually carried out to improve yield and quality. This system allows farming flexibility according to the agricultural commodity market. Over the past eighty years, the role of temporary and permanent pasture as a reserved resource of land of high soil fertility has been very successful in providing good quality arable land for various uses especially for cereal crops according to domestic demand for grain. Briggs and Courtney (1985) reported an inverse relationship between grain price and the area of land under grass.

The key economic value of herbage mixtures is the above ground biomass which enables it to be used entirely as animal feeding stuff. Although the growth pattern of a ryegrass/clover mixture involves germination, establishment, vegetative growth and seed reproduction, the main vegetative growing stage may be as long as 8 to 9 months each year in the U.K.. The root system of ryegrass is more prolific than spring barley, rape and lupin and may go as deep as 120 cm (Mackie-Dawson and Atkinson 1991) although the main root zone is within 0 to 20 cm of the soil surface. This makes it different from seed producing crops, which may be greatly influenced by drought.

The potential productivity of grassland has been recognized over the years as a result of research in yield response to nitrogen fertilizer. In temperate regions, a yield increase of about 30% may be achieved by supplying appropriate nitrogen fertilizer (Steele 1982; Steele and Vallis 1987). Levels of nitrogen application may reach to 300 - 620 kg N/ha before the yield asymptote is achieved (Morrison, Jackson and Sparrow 1980).

The quality of a ryegrass/clover mixture may be assessed by its digestibility, which is expressed by a D-value (digested organic matter over total intake organic matter). Normally, the D-value of ryegrass ranges from 0.58 to 0.75 and white clover from 0.7 to 0.8 (Osbourn 1980).

1.10 General description of soil type and climate of the experimental site

(1) Soil conditions

The experimental site was located at the Ness Botanic Gardens, Wirral, on previously cropped land of a sandy loam soil type.

The geology of the site is typical of the Wirral Peninsula with sandstone promontories protruding through glacial drift (Hulme 1983). The field site had been in continuously winter wheat production for more than four years before the trials in this thesis were conducted.

The soil of the experiment field was classified as sandy silt, one variety of sandy loam, and the nitrogen fertility index was zero. The profile of the soil can be described as follows:

Table 1.10-1. Description of the soil profile of the experimental site.

Layer	depth (cm)	General description
A horizon	0 - 15	yellowish brown, firm, sandy, roots, pebbles, earthworms
AB horizon	15 - 32	yellowish brown, firm, sandy, less roots than A, pebbles, no earthworms
B horizon	32 - 60	grayish brown, slight loose, sandy, wet, pebbles, iron and manganese nodules
C horizon	60 - 100	white grey, loose, sand, very wet, pebbles, iron and manganese nodules

Place: Ness Botanic Gardens. Date: 7/2/1989.
Surveyor: J. Guo. Present crop: fallow.
Pit: No. 1. Film: No. 4--6.
Parent material: Coombe boulder sandy silt deposit.

The basal N, P, K contents of the soils at the experimental site and used in the pot and lysimeter experiments are listed in Table 1.10-2.

Table 1.10-2. N, P, K contents (mean ± SEM) of the soils for the experiments and their indices (MAFF 1983), (Ex A N = Extractable ammonium nitrogen mg/100g soil, Ex N N = Extractable nitrate and nitrite nitrogen mg/100g soil, Ex P = Extractable phosphorus ppm, Ex K = Extractable potassium ppm).

	Site 1	Site 2	Soil 1	Soil 2
Total N %	0.187 ± 0.015	0.186 ± 0.017	0.177 ± 0.014	0.169 ± 0.021
Ex A N	0.65 ± 0.09	0.67 ± 0.13	0.67 ± 0.04	0.89 ± 0.55
Ex N N	1.50 ± 0.24	0.34 ± 0.23	1.44 ± 0.10	0.23 ± 0.55
Index (N)	0	0	0	0
Ex P	19.28 ± 5.67	19.01 ± 4.40	17.15 ± 2.99	56.81 ± 14.64
Index (P)	2	2	2	4
Ex K	79.0 ± 6.9	77.13 ± 7.25	88.2 ± 11.0	179.9 ± 9.7
Index (K)	1	1	1	2

Site 1 was the site for field experiment F1EX89 and F1EX90.
Site 2 was the site for field experiment F2EX90 and F2EX91.
Soil 1 was used for the lysimeter trials.
Soil 2 was a commercial soil (John Innes seed compost) for experiments PE190 and PE290.

(2) Climatic conditions at the experimental site

The overall description of the climate at the experimental site is temperate being relatively moist in winter and slightly dry in spring and summer.

Typically moist south-westerly air currents advance towards the Wirral over the Welsh Hills (Clwyd), where considerable precipitation occurs, creating a "rain shadow" in south-west Wirral. Rainfall records for Neston between 1879 and 1942 show a maximum yearly total of 805.18 mm and a minimum of 650.24 mm, with an average over the 73-year period of 711.2 mm per annum (Hulme 1983). The district may rank as one of the driest on the west coast of England. If comparisons are made with the Cheshire plain further inland, Ness Botanic Gardens experiences fewer and generally less severe frosts. The prevailing wind also limits the spread of industrial haze in the direction of the Gardens (Hulme 1983).

1.11 Thesis structure

Chapter 2 compares yields of spring sown barley, lupin, oilseed rape and a ryegrass/clover mixture in response to N fertilizer under field conditions.

A comparison of yields of autumn sown wheat, oilseed rape, a ryegrass/clover mixture and spring sown lupin in response to N fertilizer is described in Chapter 3.

Chapter 4 examines the growth patterns of wheat, lupin, oilseed rape and a ryegrass/clover mixture and the changes of nitrogen in plant and soil at different growing stages under controlled conditions.

The influence of crops in relation to N fertilizer application on nitrogen leaching and the concentration of nitrate in the leachate is considered in Chapter 5.

Chapter 6 provides a synthesis.

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CHAPTER 2 COMPARISON OF YIELDS IN RESPONSE TO NITROGEN FERTILIZER IN TWO SUCCESSIVE CROPPING SEASONS

2.1 Introduction

Spring sown crops are grown when unfavorable weather, soil conditions or previous crop prevents an autumn sowing. A two year experimental programme was designed to compare yield responses to N fertilizer in spring sown barley, lupin, rape and a ryegrass/clover mixture to develop an understanding of variation in yield performance amongst the crops.

In order to obtain a full range of responses, the four crops were grown over seven levels of nitrogen fertilizer application, the upper level being determined by the crop in question. This upper limit was chosen to exceed the normal fertilizer recommendation (MAFF 1983) with the lowest level receiving no nitrogen fertilizer. All together, seven levels were used to establish the response curve of crop yield to nitrogen. Previous research suggests that six to seven levels of nitrogen fertilizer may be adequate for statistical purpose. For example, Morrison, Jackson and Sparrow (1980) obtained a curve of ryegrass in response to nitrogen with six levels of fertilizer application (including zero application). The rates were in the range 150 to 750 Kg N per hectare, increasing by 150 Kg N at a time. Another example is that of Needham and Boyd (1976) who published the data of seventeen experiments with spring barley testing seven application rates of nitrogen. In their study the fertilizer application was in the range 0 to 150 Kg N per hectare, increasing by 25 Kg N at a time.

Since it is known that these crops differ considerably in growth and phenology, it is difficult to apply a common set of levels of nitrogen application over a finite range in one experiment. In practice, the annual rates of nitrogen fertilizer depend on the requirements of different crops and in consequence individual ranges were chosen for each crop in question.

2.2 Comparison of yields in response to N fertilizer among barley, lupin, rape and a ryegrass/clover mixture in field experiment (F1EX89)

2.2.1 Materials and methods

Experiment design

A field experiment, coded F1EX89, was set up to examine the yield of spring barley, spring rape, spring lupin and a ryegrass/clover mixture at each of seven levels of nitrogen application, giving 28 treatments. The experimental design was a randomized complete block (3 blocks) with three replicates, giving a total number of eighty four plots. Individual plots of 12 square metres were established with guard areas around a central harvested area of two metres by two metres. Plots were separated by 1 m paths to minimize the effects of nitrogen movement through surface water runoff and soil drainage.

To ensure a sufficiency of phosphate and potassium, 828 g of ICI No 12 fertilizer (N, P, K, = 0, 8.73%, 26.56%) were uniformly applied to each plot just before crop sowing by raking into the top 15 cm of soil. These applications are equivalent to 60 kg of P and 183 kg of K per hectare. The levels of P and K application exceeded the recommended levels (MAFF 1983) for the four crops. Nitrogen was supplied as 'NITRAM' (NH_4NO_3, 34.5% N) as summarized in the following tables.

Table 2.2.1-1. Experimental details: spring sown barley in experiment (F1EX89).

Crop growth Stage	Fertilizer treatment (N levels) 1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	21	42	63	84	105	126
Established(nitram g/plot)	0	118	236	354	473	591	709
Total (nitram g/plot)	0	139	278	417	557	696	835
Total (kg N/ha)	0	40	80	120	160	200	240

Variety: REGATTA. Sowing date: 26 - 29th March 1989.
Sowing depth: 25 - 35 mm. Seed rate: 450 seeds/m^2.
Growing period: 123 days. Harvesting date: 25/7/1989.
Plot size: 12 m^2.

Table 2.2.1-2. Experimental details: spring sown lupin in experiment (F1EX89).

Crop growth stage	Fertilizer treatment (N levels) 1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	17	35	52	70	87	104
Established (nitram g/plot)	0	17	35	52	70	87	104
Total (nitram g/plot)	0	34	70	104	140	174	208
Total (kg N/ha)	0	10	20	30	40	50	60

Variety: PRIMORSK. Sowing date: 29 - 31st March 1989.
Sowing depth: 25 - 35 mm. Row spacing: 15 - 20 cm.
Growth period: 156 days. Seed rate: 75 seeds/m^2.
Harvesting date: 2nd September 1989. Plot size: 12 m^2.

Table 2.2.1-3. Experimental details: spring sown rape in experiment (F1EX89).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	31	63	94	125	157	188
Established (nitram g/plot)	0	178	354	532	710	886	1064
Total (nitram g/plot)	0	209	417	626	835	1043	1252
Total (kg N/ha)	0	60	120	180	240	300	360

Variety: OPUS.
Seed rate: 250 seeds/m^2.
Harvesting date:13th August 1989.
Plot size: 12 m^2.
Sowing date: 1st April 1989.
Sowing depth: 15 - 20 mm.
Growth period: 135 days.

Table 2.2.1-4. Experimental details: spring sown ryegrass/clover mixture in experiment (F1EX89).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	33	66	99	132	165	198
Established (nitram g/plot)	0	20	40	60	80	100	120
After 1st cut (nitram g/plot)	0	33	66	99	132	165	198
After 2nd cut (nitram g/plot)	0	33	66	99	132	165	198
After 3rd cut (nitram g/plot)	0	33	66	99	132	165	198
After 4th cut (nitram g/plot)	0	22	44	66	88	110	132
Total (nitram g/plot)	0	174	348	522	696	870	1044
Total (kg N/ha)	0	50	100	150	200	250	300

Varieties: Antrim (perennial ryegrass). Seed rate 30 g/plot.
RVP (Italian ryegrass). Seed rate 30 g/plot.
Grasslands Huia (white clover). Seed rate 25 g/plot.
Sowing date: 3 - 6th April 1989. Sowing depth: 20 - 30 mm.
Row spacing: random. Plot size: 12 m^2.

Harvesting date:	1st cut	2nd cut	3rd cut	4th cut
(year of 1989)	25 - 28th Jun.	2 - 5th Aug.	2 - 5th Sep.	15th Oct.

Experiment procedures

The experimental site had been cropped previously with winter wheat for three successive seasons and left fallow from September 1988.

Before sowing, the experimental area was sprayed with the herbicide glyphosate (Round-up 100 ml in 20 litres water for 500 square metres) and, after a week, the soil was ploughed and levelled by disc harrow.

Crops were sown by hand in late March/early April 1989 at the depths indicated in Tables 2.2.1-1 to 2.2.1-4.

During the course of the experiment, weeds on the pathways were controlled by herbicide (Round-up) and weeds in the plots were carefully pulled out manually.

Harvesting

The mixture of ryegrass and white clover (21 plots) was harvested just above ground over an area of 4 square metres on four occasions from June to October (Table 2.2.1-4). Subsamples of about 500 g fresh biomass were taken randomly from each plot and dried at 100^0 C for 18 hours for estimation of water content and a further 50 g sample of each plot dried at 65^0 C for two days for subsequent nitrogen assessment. Yield per plot was expressed as the cumulative total.

Spring barley, spring rape seed and spring lupin were harvested at the end of the experiment over an area of 4 square metres. For barley after weighing, about five hundred grammes of biomass from each plot was sampled and dried at 100^0 C for 18 hours to estimate dry matter. Subsequently, seed per sample was measured and the seed yield per plot was estimated.

Lupin and rape plants were air-dried after harvesting the central 4 square metres of each plot and seeds then separated from plants. Around 500 grammes of stem and 100 grammes of seed were subsampled from each plot and dried at 100^0 C for 18 hours to determine dry matter. A further 50 g sample of each plot was taken separately both from stem and seed material, and dried at 65^0 C for two days for subsequent nitrogen assessment.

Dried samples for nitrogen assessment were stored at laboratory temperature until analysis.

Nitrogen analysis

Top soil (0 to 15 cm depth) was sampled for total N, extractable N, extractable P and K before the experiment. Crops were sampled for N assessment at the end of the experiment. Total nitrogen in the sample was converted to ammonium-nitrogen by digestion with sulphuric acid and sodium sulphate with a copper-selenium catalyst. The ammonium-nitrogen in solution was determined by autoanalysis and detailed methods are given in Appendix A. Inorganic nitrogen in soil (NH_4-N, NO_2-N or NO_3-N) was extracted with 6% (w/v) sodium chloride. The nitrogen in solution was then determined (Appendix A). Extractable phosphorus in soil was extracted at 20 ± 1^0 C with a sodium bicarbonate solution of pH 8.5. The concentration of the blue complex produced by the reduction, with ascorbic acid, of the phosphomolybdate formed when acid ammonium molybdate reacts with phosphate was measured spectrophotometrically at 880 nm. Extractable potassium in soil was extracted with 1 M ammonium nitrate. The concentration of potassium in the extract was determined by flame photometry.

In the comparison of yields, biomass is defined as the yield of above ground plant parts including leaves, stems and seeds dried at 100^0 C for 18 hours. Economic yield, dried at 100^O C for 18 hours, is defined as the seed yield for barley, lupin, and rape seed, and the yield of herbage for the ryegrass/clover mixture. Crude protein content was calculated from nitrogen content (%) of the economic yield multiplied by a factor of 6.25 (Helmprecht and Friedman 1977).

The choice of model of yield-nitrogen relationship in this thesis

An essential technique used in this thesis was the description of yield nitrogen relationships and the choice of a common model was based on a detailed analysis of available options. This analysis utilised data generated by experiments and the process of model evaluation is presented here.

Equations (1), (7), (9) and (10) in section 1.5, which in this thesis are named model 1, model 2, model 3 and model 4 in sequence, were fitted to the data from the field experiment (F1EX89). The fitted curves for each equation are compared in Figs 2.2.1-1 to 4. Parameter estimation was made using SAS non linear procedures (SAS Institute 1985).

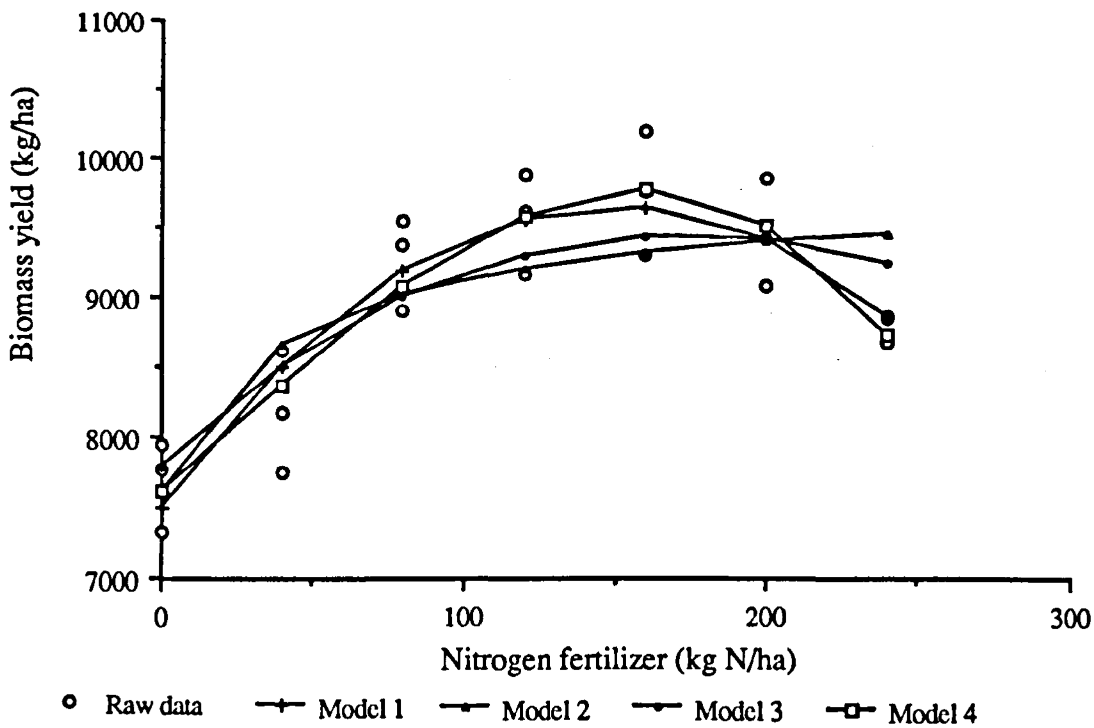

Fig 2.2.1-1. Comparison of four mathematical models to describe barley biomass in response to N fertilizer application in the field experiment (F1EX89).

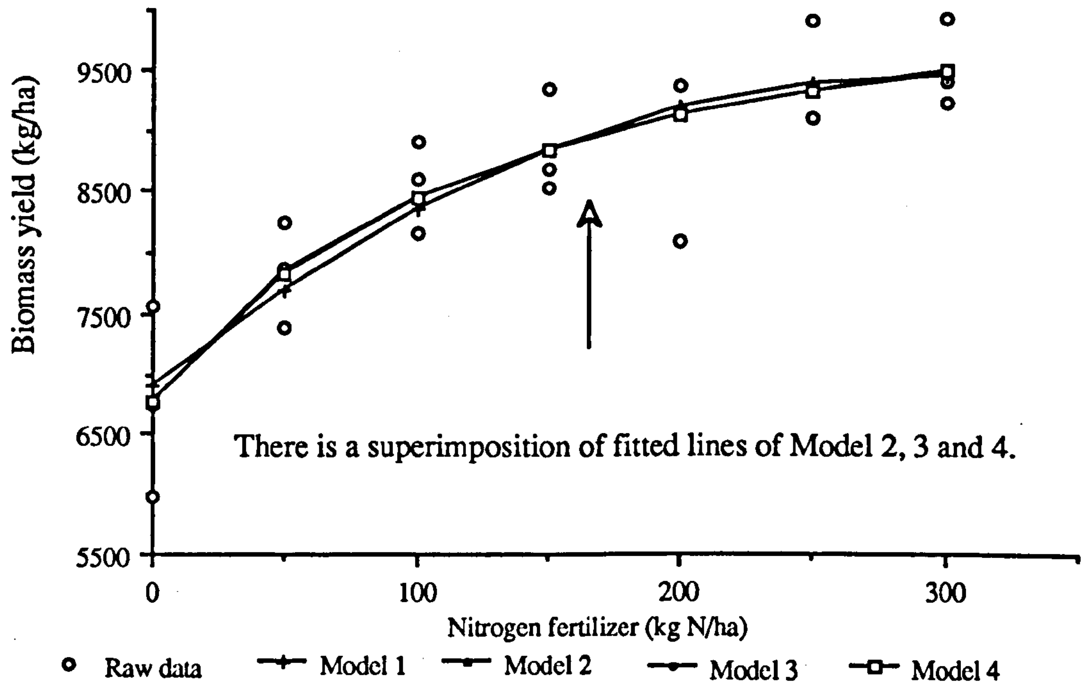

Fig 2.2.1-2. Comparison of four mathematical models to describe the biomass of ryegrass/clover mixture in response to N fertilizer application in the field experiment (F1EX89).

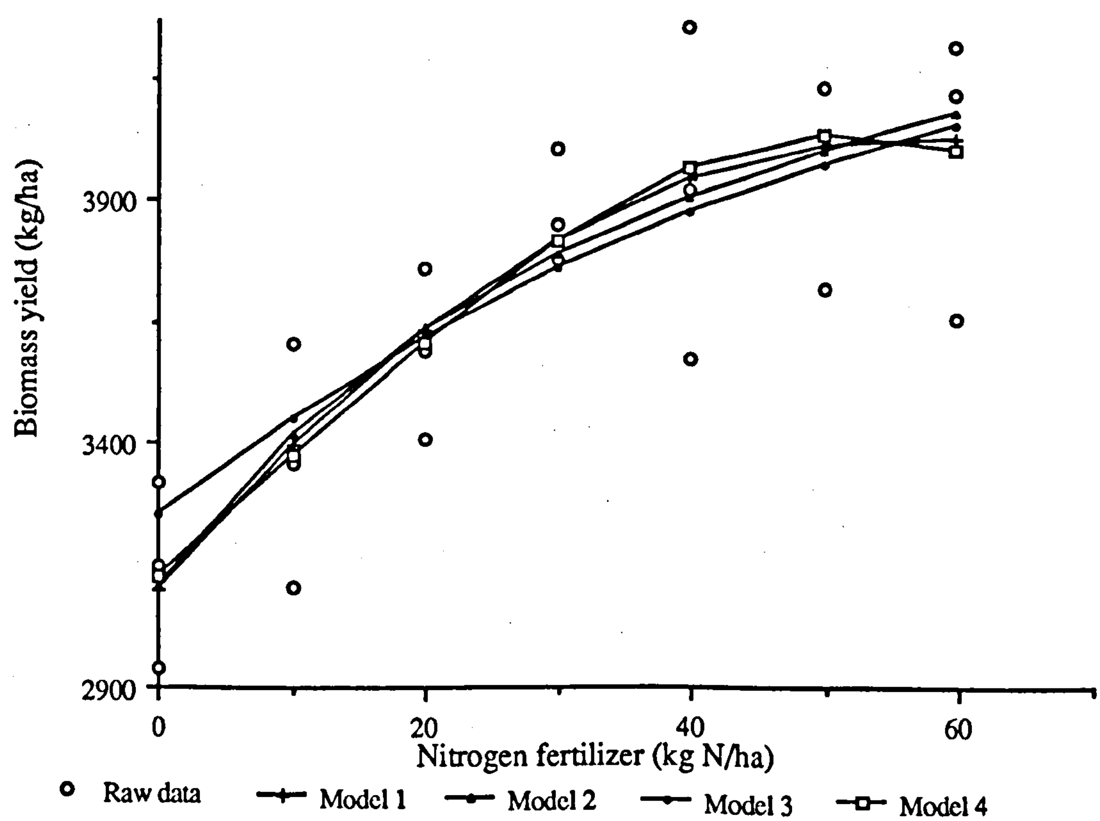

Fig 2.2.1-3. Comparison of four mathematical models to describe lupin biomass in response to N fertilizer application in the field experiment (F1EX89).

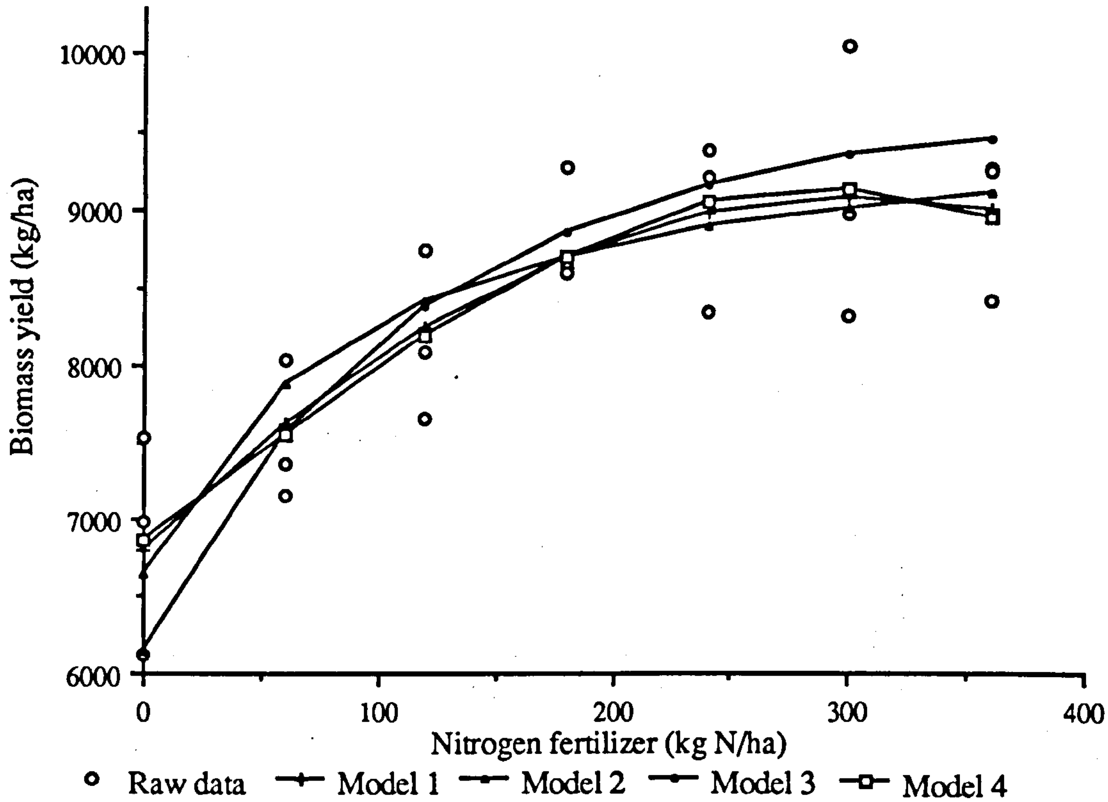

Fig 2.2.1-4. Comparison of four mathematical models to describe rape biomass in response to N fertilizer application in the field experiment (F1EX89).

After model fitting, the predicted values were examined following an evaluation procedure of the most appropriate model. The 'best model' was not only defined as providing a good fit for every crop in general (least residual mean square), but also as giving the best predicted yield at each level of fertilizer application.

The criterion used for judging the fit was the residual sum of squares (Table 2.2.1-5) and the total point ranking. The point ranking was derived in such a way that the differences (absolute value) between predicted yield and observed yield were ranked in descending order, and then amongst the four models, the largest difference was given 1 point, and smallest difference given 4 points with intermediate values given 2 or 3 point accordingly. By summing the points for each model at each level of fertilizer application, a sub-total point was obtained (Table 2.2.1-6). Thus, the highest sub-total point indicates a closest-to-mean fitting at most levels of fertilizer application.

Table 2.2.1-5. Illustrative residual sum of squares after model fitting for each crop and model. Data from the field experiment (F1EX89). * indicates the lowest residual sum of squares amongst the models described in the text. (G/C = ryegrass/clover).

Crops	Model 1	Model 2	Model 3	Model 4
Spring barley	2310002	4968684	3526146	2091336*
G/C mixture	4380941	4067579*	4067582	4067579*
Spring lupin	925685	963275	1004224	911244*
Spring rape	5083275	5409210	5342835	5025656*

Table 2.2.1-6. Illustrative comparison of four models by point ranking for each crop classified at each level of nitrogen application. Data from the field experiment (F1EX89). * indicates the lowest point ranking amongst the models described in the text. (G/C M = ryegrass/clover mixture).

		Nitrogen level							
model	crop	1	2	3	4	5	6	7	sub-total of points
1	barley	1	2	4	4	3	3	3	20
2	barley	2	1	2	1	1	2	1	10
3	barley	3	3	1	2	2	4	2	17
4	barley	4	4	3	3	4	1	4	23*
1	G/C M	1	1	1	2	1	4	1	11
2	G/C M	2	2	4	4	2	2	3	19
3	G/C M	3	3	3	3	3	1	2	18
4	G/C M	4	4	2	1	4	3	4	22*
1	lupin	2	3	1	4	3	4	3	19
2	lupin	3	2	2	2	4	2	1	16
3	lupin	1	1	3	1	2	1	2	11
4	lupin	4	4	4	3	1	4	4	24*
1	rape	3	2	3	1	4	3	3	19
2	rape	2	1	1	2	2	2	2	12
3	rape	1	3	2	4	1	1	1	13
4	rape	4	4	4	3	3	4	4	26*

Detailed comparison showed that the inverse quadratic polynomial model, equation (10), model 4, gave the best fit (least residual sum of square) for each crop and gave a predicted yield closest to the observed yield at most levels of nitrogen application. All models provided a good statistical fit to the data for each crop.

As a result of this assessment, equation (10) was chosen for fitting the data from the experiments in Chapters 2, 3 and 5.

Parameter estimation for equation (10) in some instances yielded values for the coefficient b_2 of zero. In such circumstances this parameter gives no predictive information and was dropped in final model fitting. In certain circumstances, to achieve an adequate fit it became necessary to fix the value of b_2 after initial iteration. The relevant contribution of b_2 to predicted values is illustrated in Fig 2.2.1-5 and Table 2.2.1-7.

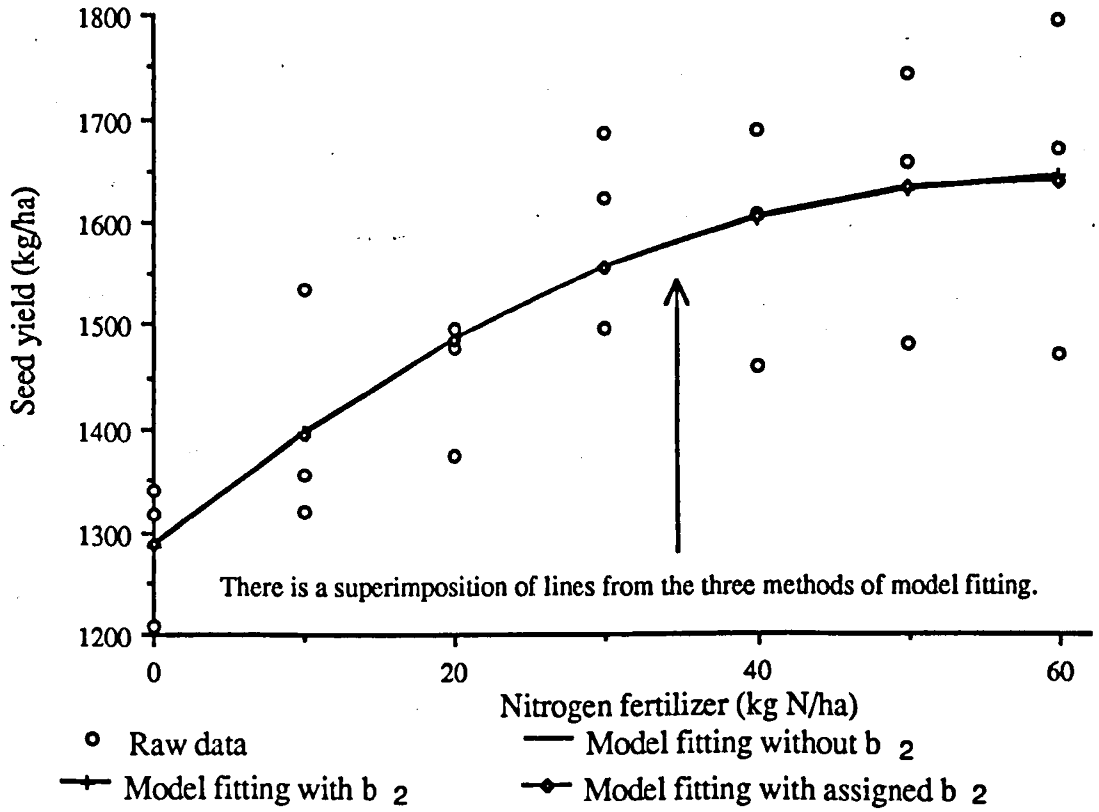

Fig 2.2.1-5. Comparison of three methods of model fitting concerning parameter b_2, using lupin seed yield from experiment (F1EX89).

Table 2.2.1-7. Illustrative comparison of methods of fitting equation (10) concerning parameter b_2, using the data of barley biomass in response to nitrogen from the field experiment (F1EX89). (PT = Parameter, SE = Standard error, R M S = Residual mean square).

	Model including b_2		Model without b_2		Model assigned b_2	
	PT	SE	PT	SE	PT	SE
b_0	7479	216	7482	197	7483	188.7
b_1	29.854	8.12	29.694	4.5	28.83	5.87
b_2	0	7.0e-5	0	0	9.0e-5	0
b_3	1.1e-5	5.6e-6	1.1e-5	2.1e-6	1.1e-5	3.5e-6
R M S	149822		141482		116185	

2.2.2 Results of field experiment (F1EX89)

2.2.2.1 Biomass and economic yields

The total biomass of barley, lupin, rape and the ryegrass/clover mixture differed very significantly ($p < 0.01$) from one other at harvest (Table 2.2.2-1). There was a highly significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass yields of the crops in general, and this treatment had differential effects on the yields of the crops ($P < 0.04$). No differences amongst blocks were apparent ($p > 0.05$), possibly due to the past cropping practice with winter wheat for three successive seasons resulting in the residual soil fertility being homogeneous across the experimental area.

Table 2.2.2-1. Analysis of variance of biomass yield of spring sown barley, lupin, rape and ryegrass/clover mixture in experiment (F1EX89).

Source	DF	Sum of squares	F*	P_{HO}
Block	2	243661.2	0.59	0.5597
Crop	3	384322323.7	616.84	0.0001
Fertilizer	6	36549101.4	29.33	0.0001
Crop*fertilizer	18	6984329.5	1.87	0.0399
Error	54	11214857.5		
Total	83	439314273.2		

* F = Ratio of mean square treatment to error mean square, where mean squares are sums of squares divided by degrees of freedom.

Table 2.2.2-2. Analysis of variance of economic yields of spring sown barley, lupin, rape and ryegrass/clover mixture in experiment (F1EX89).

Source	DF	Sum of squares	F	P_{HO}
Block	2	74880.5	0.33	0.7219
Crop	3	643469123.5	1878.55	0.0001
Fertilizer	6	10854408.0	15.84	0.0001
Crop*fertilizer	18	9100734.5	4.43	0.0001
Error	54	6165644.2		
Total	83	669664790.7		

Analysis of variance indicated a similar pattern of significant effects for economic yield (Table 2.2.2-2).

Comparison of mean crop yield pooling over fertilizer showed that the biomass production of rape and the ryegrass/clover mixture was statistically similar (individual

$LSD_{0.05}$ = 282). However the biomass of the ryegrass/clover mixture was 5.5% less than that of barley and 2.3 times higher than that of lupin, while the biomass of rape was 7.7% less than that of barley and 2.3 times greater than that of lupin.

Over the four crops, the average economic yield of the ryegrass/clover mixture, pooling over N fertilizer application, was the highest (8549 kg/ha). It was approximately 2.4 times higher than that of barley (3510 kg/ha), 4 fold higher than that of rape (2114 kg/ha) and 5.6 times greater than that of lupin (1514 kg/ha) (Fig 2.2.2-1).

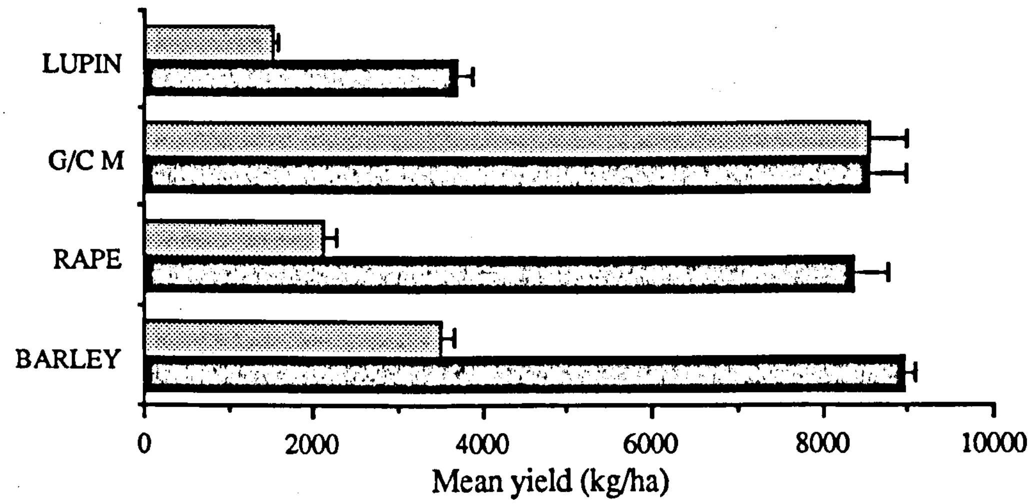

Fig 2.2.2-1. Comparison of crop yields, using pooled data over N fertilizer application (experiment F1EX89). Confidence limits are standard errors of the mean. G/C M = ryegrass/clover mixture.

■ biomass, LSD = 282 kg/ha ▨ Economic yield, LSD = 224 kg/ha

2.2.2.2 Yield responses to nitrogen fertilizer

Equation (10) (Chapter 1) was used to mathematically describe the yield-nitrogen relationship. Parameter estimates and their standard errors of this equation are given in Table 2.2.2-3, fits being achieved by non linear regression (SAS Institute 1985). In all cases R^2 values were close to unity indicating good statistical fit of the model.

Table 2.2.2-3. Parameter estimates and their standard errors of the yield nitrogen response for each crop using field data over the period March 1989 to October 1989. (SE = Standard error of parameter estimate, R^2 = coefficient of determination, G/C M = ryegrass/clover mixture, B = biomass yield, E = economic yield, Dry Matter kg/ha).

Crops	b_0	b_0 SE	b_1	b_1 SE	b_2	b_2 SE*	b_3	b_3 SE	R^2
Barley B	7483	189	28.83	5.9	-9.0e-5	0	1.1e-5	3.5e-6	0.9988
Barley E	2985	135	3.34	2.8	-2.1e-3	0	1.1e-5	3.3e-6	0.9952
Lupin B	3101	115	31.35	9.0	0.0	0	6.6e-5	3.7e-5	0.9968
Lupin E	1288	51.7	8.84	3.9	-1.9e-3	0	6.2e-5	3.9e-5	0.9961
Rape B	6800	272	14.61	3.7	0	0	2.6e-6	1.1e-6	0.9966
Rape E	1730	139	3.35	1.8	0	0	2.0e-6	2.2e-6	0.9860
G/C M	6774	270	80.50	40.5	7.5e-3	4.4e-3	0	0	0.9972

* Where estimates of b_2 SE are zero, b_2 was fixed in the regression.

(1). The response of barley to nitrogen

The relationship of barley yield to increasing nitrogen is illustrated in Fig 2.2.2-2.

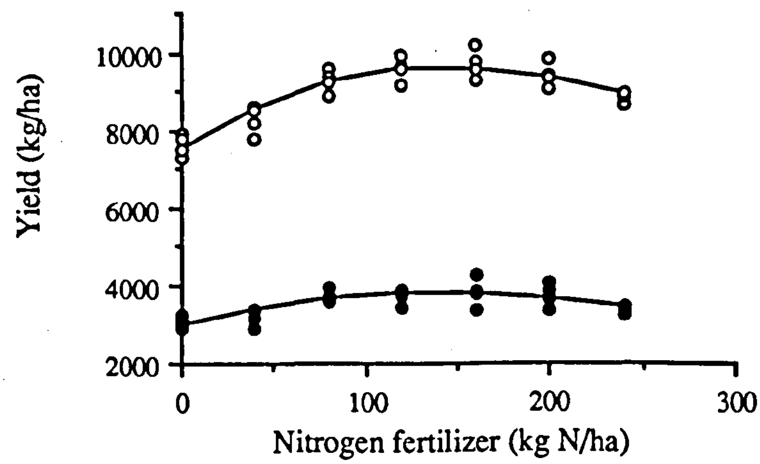

Fig 2.2.2-2. The yield of barley in response to nitrogen fertilizer (experiment F1EX89).

- o Biomass —o— Biomass fitted curve
- • Seed yield —•— Seed yield fitted curve

The fitted curves of the biomass (kg/ha) and seed yield (kg/ha) are described by equations:

$$\text{Biomass} = \frac{7483 + 28.825N}{1 - 0.00009N + 0.000011N^2}$$

$$\text{Seed yield} = \frac{2985 + 3.342N}{1 - 0.00211N + 0.000011N^2}$$

where N is nitrogen fertilizer in kg N/ha.

The maximum biomass yield of 9575 kg/ha was observed at a nitrogen application of 141 kg N/ha which was close to the corresponding nitrogen level of 136 kg N/ha for maximum grain yield (3753 kg/ha).

The economic response (kg/ha) (defined in Chapter 1, section 1.5) was calculated to be 3726 kg/ha of grain obtained at nitrogen level of 112 kg N/ha. This is 99% of the maximum yield observed, but was achieved at 82% of fertilizer requirement for maximum yield.

(2). The response of ryegrass/clover mixture to nitrogen

The relationship of the yield of the ryegrass/clover mixture to fertilizer N is illustrated in Fig 2.2.2-3.

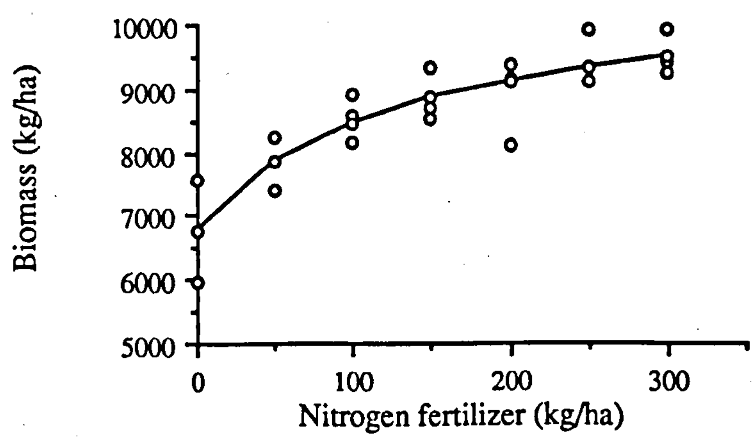

Fig 2.2.2-3. The biomass of ryegrasss/clover mixture in response to nitrogen fertilizer in experiment (F1EX89).

o Biomass —o— Biomass fitted curve

The fitted curve of the biomass (kg/ha) is described by equation

$$\text{Biomass} = \frac{6774 + 80.497N}{1 + 0.007539N}$$

where N is nitrogen fertilizer in kg N/ha.

Equation (10) gave a good fit ($R^2 = 0.9972$) to the data and parameter estimates of b_3 of zero, which implies that the maximum response of the ryegrass/clover mixture to nitrogen fertilizer could not be obtained from the model, as it also indicated by the quadratic nature of the yield response.

The economic response, estimated at a nitrogen level of 338 kg N/ha, was calculated to be 9577 kg/ha. Y_{10} (8430 kg/ha) was obtained at 95 kg N/ha.

(3). The response of lupin to nitrogen

Fig 2.2.2-4 shows the relationship of lupin yield with nitrogen fertilizer.

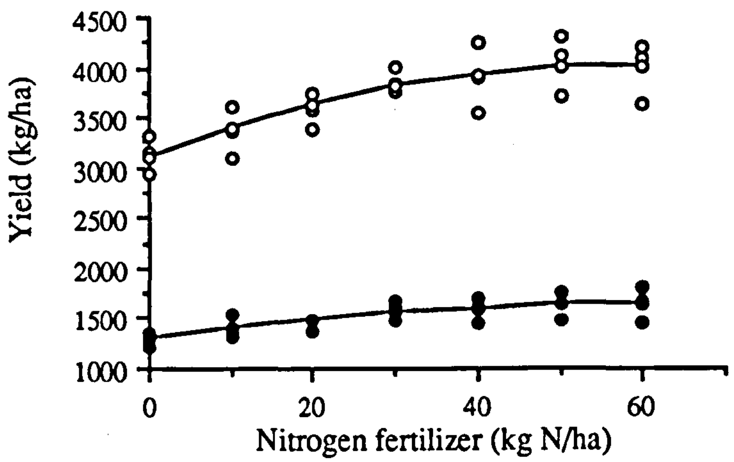

Fig 2.2.2-4. The yield of lupin in response to nitrogen fertilizer in experiment (F1EX89).

○ Biomass —○— Biomass fitted curve
● Seed yield —●— Seed yield fitted curve

The fitted curves of the biomass (kg/ha) and seed yield (kg/ha) are as follows

$$\text{Biomass} = \frac{3101 + 31.348N}{1 + 0.000066N^2}$$

$$\text{Seed yield} = \frac{1288 + 8.844N}{1 - 0.001902N + 0.000062N^2}$$

where N is nitrogen fertilizer in kg N/ha.

The maximum biomass yield of 4026 kg/ha was observed with a nitrogen application of 59 kg N/ha which coincided with the nitrogen level for the maximum seed yield of 1640 kg/ha. The economic response, at nitrogen level of 51 kg N/ha, was 1634 kg/ha of seed, being 99.6% of maximum yield.

(4). The response of rape to nitrogen

The observed yield responses to nitrogen for rape are given in Fig 2.2.2-5.

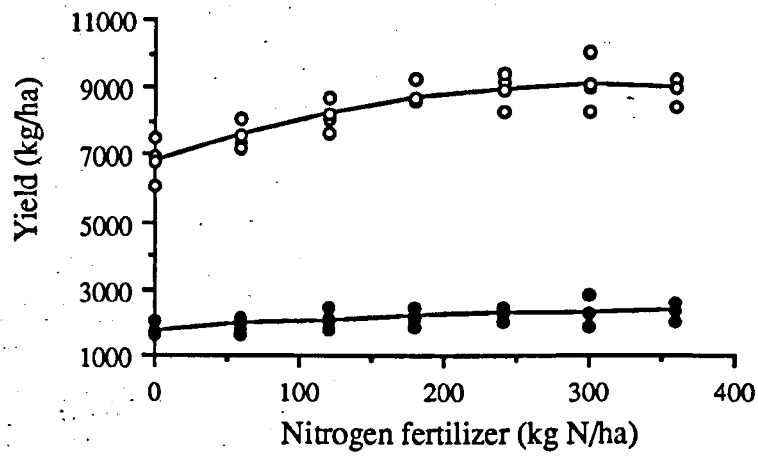

Fig 2.2.2-5. The yield of rape in response to nitrogen fertilizer in experiment (F1EX89).

Response lines for biomass (kg/ha) and seed yield (kg/ha) are described by the equations

$$\text{Biomass} = \frac{6800 + 14.614N}{1 + 0.0000026N^2}$$

$$\text{Seed yield} = \frac{1730 + 3.347N}{1 + 0.000002N^2}$$

where N is nitrogen fertilizer in kg N/ha.

The maximum biomass yield was 9065 kg/ha of dry matter, derived at nitrogen level of 310 kg N/ha. The maximum seed yield, seen at nitrogen level of 359 kg N/ha, was 2331 kg/ha. The economic response (2236 kg/ha) was obtained at a nitrogen level of 210 kg N/ha.

2.2.2.3 Nitrogen content and crude protein yield.

(1) Total nitrogen content

The nitrogen content (%) of the seed and straw or herbage was significantly different ($p < 0.01$) amongst crops, but no statistical evidence was found to indicate that N fertilizer influenced the N content of the crops ($p > 0.05$, Table 2.2.2-4). Scatter graphs, however, showed some positive trends in nitrogen content with increasing nitrogen application for both barley and the ryegrass/clover mixture (Fig 2.2.2-5).

Table 2.2.2-4. Analysis of variance of N content (%) of the seed (or herbage) and straw of the four crops in the experiment (F1EX89).

	Source	DF	Sum of squares	F	P_{HO}
Economic parts	Crop	3	158.67	472.90	0.0001
	Fertilizer	6	0.97	1.44	0.2162
	Crop*fertilizer	18	1.12	0.56	0.9139
	Block	2	0.04	0.19	0.8252
	Error	54	6.04		
	Total	83	166.85		
Straw (stem)	Crop	3	24.75	72.89	0.0001
	Fertilizer	6	1.28	1.89	0.0991
	Crop*fertilizer	18	0.71	0.35	0.9918
	Block	2	0.12	0.54	0.5845
	Error	54	6.11		
	Total	83	32.97		

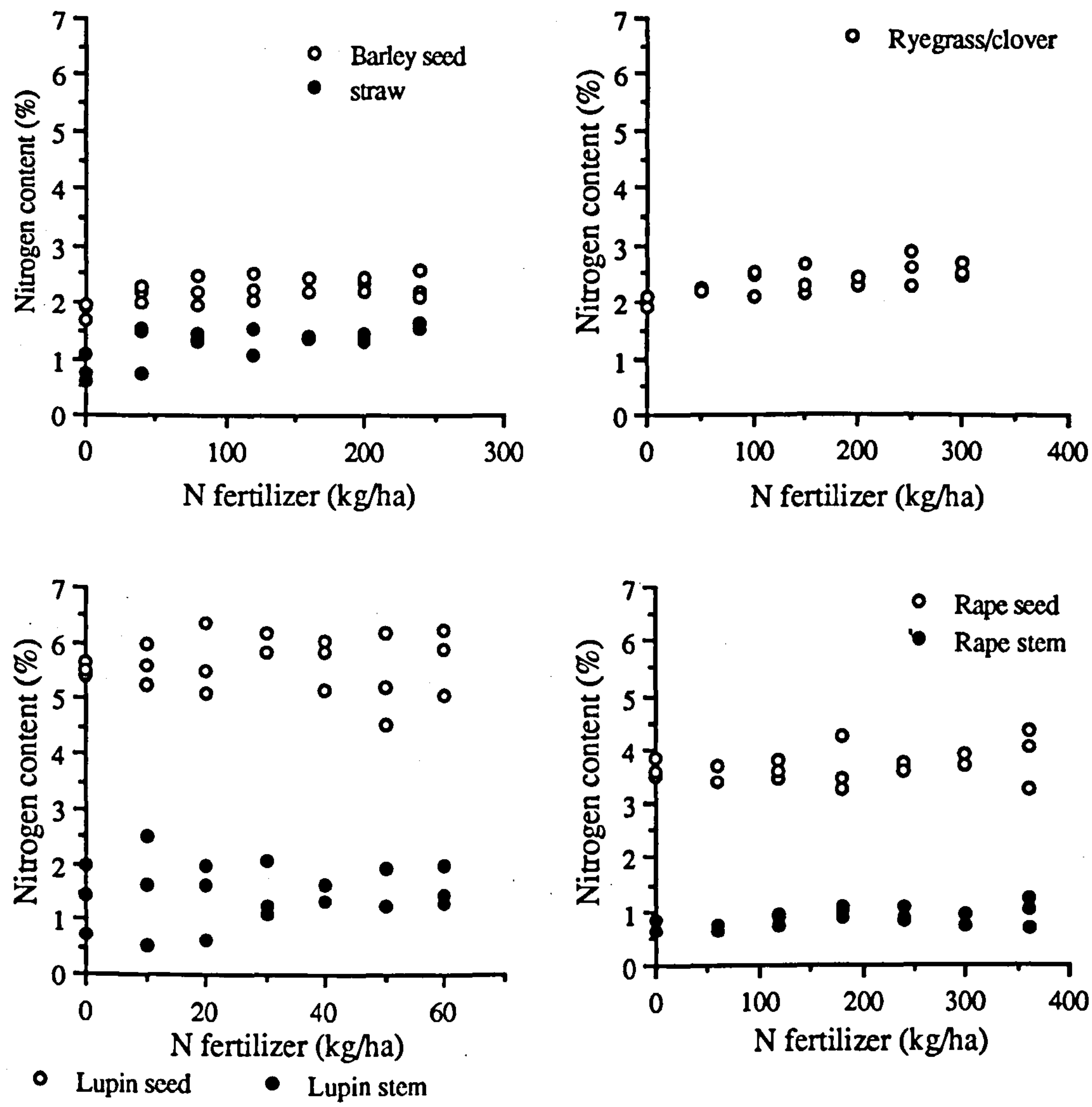

Fig. 2.2.2-5. The influence of nitrogen fertilizer application rate on nitrogen content (%) of the crop components in the experiment (F1EX89).

The average nitrogen content (pooled over N fertilizer levels) of the economic parts and straw (stem) of the four crops is listed in Table 2.2.2-5.

Table 2.2.2-5. Average nitrogen content (mean % ± SEM) of the crops, pooled data over nitrogen fertilizer levels, in experiment F1EX89. G/C M = ryegrass/clover mixture.

	Barley	Lupin	Rape	G/C M
Economic parts	2.03 ± 0.22	5.64 ± 0.47	3.70 ± 0.28	2.62 ± 0.24
Straw (stem)	1.28 ± 0.29	1.48 ± 0.50	0.87 ± 0.15	

(2) Crude protein yield

An average crude protein content (%) (pooled data over fertilizer application) of each crop was estimated by multiplying nitrogen content (%) by a factor of 6.25 (Helmprecht and Friedman 1977). The economic protein yield was calculated from the economic yield multiplying by its protein content (%) (Table 2.2.2-6).

Table 2.2.2-6. Average crude protein content (%) and economic protein yield (Mean % ± SEM) of the four crops, pooled data over nitrogen fertilizer levels, in experiment F1EX89. G/C M = ryegrass/clover mixture, $LSD_{0.05}$ = 38 kg/ha.

	Barley	Lupin	Rape	G/C M
Protein content (%)	12.69	35.25	23.13	16.38
Protein yield (kg/ha)	445 ± 10	534 ± 12	489 ± 17	1400 ± 36

The ryegrass/clover mixture gave the highest crude protein yield, followed by lupin and rape with barley giving the lowest crude protein yield.

2.3 Comparison of yields in response to nitrogen fertilizer among the crops in field experiment (F1EX90)

2.3.1 Materials and Methods

Experiment design

The field experiment from October 1989 to September 1990, coded F1EX90, was simply a partly repeated experiment of F1EX89 at the same site and used the same plots to examine yield performance in the following year.

The treatments in this experiment were the same as in spring 1989, examining the growth of spring sown barley, rape, lupin and the ryegrass/clover mixture at each of seven levels of nitrogen application, giving 28 treatments with three replicates. The ryegrass/clover plots were continued from experiment F1EX89 whereas all other plots were resown with the same crop at the same density. The experimental layout was the same as in spring 1989, giving a total number of eighty four plots. The harvested area of each plot was reduced to one metre by one metre. One metre guard areas were established around each plot giving a overall plot area 4 square metres. To ensure sufficient supply of phosphate and potassium, 276 g of ICI No 12 fertilizer (N, P, K, = 0, 8.73%, 26.56%), were uniformly applied to each plot just before sowing by raking into the top 15 cm of soil except for top-dressing on the plots of the ryegrass/clover mixture. The amount of P and K applied was the same as that in the previous year. The N fertilizer used in the experiment was 'NITRAM' (NH_4NO_3, 34.5% N).

Specific details for each crop are summarized in the Tables 2.3.1-1 to 2.3.1-4. Different amounts of nitrogen per plot, but the same proportions as in F1EX89, were applied in this experiment because plots were smaller than in previous experiment (F1EX89).

Table 2.3.1-1. Experimental details: spring sown barley in field experiment (F1EX90).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	7	14	21	28	35	42
Established (nitram g/plot)	0	39	78	118	156	197	236
Total (nitram g/plot)	0	46	92	139	186	232	278
Total (kg N/ha)	0	40	80	120	160	200	240

Variety: REGATTA.
Sowing depth: 25 - 35 mm.
Growing period: 140 days.
Plot size: 4 m^2.

Sowing date: 5th to 7th March 1990.
Seed rate: 450 seeds/m^2.
Harvesting date: 25 - 27th July 1990.

Table 2.3.1-2. Experimental details: spring sown lupin in field experiment (F1EX90).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	6	12	18	24	30	36
Established (nitram g/plot)	0	6	12	18	24	30	36
Total (nitram g/plot)	0	12	24	36	48	60	72
Total (kg N/ha)	0	10	20	30	40	50	60

Variety: PRIMORSK.
Row spacing: 15 - 20 cm.
Growing period: 162 days.
Plot size: 4 m^2.

Sowing date: 5th to 7th March 1990.
Seed rate: 75 seeds/m^2.
Harvesting date: 25 - 28th Aug. 1990.

Table 2.3.1-3. Experimental details: spring sown rape in field experiment (F1EX90).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	11	22	33	44	55	66
Established (nitram g/plot)	0	59	117	176	234	293	351
Total (nitram g/plot)	0	70	139	209	278	348	417
Total (kg N/ha)	0	60	120	180	240	300	360

Variety: OPUS.
Sowing depth: 15 - 20 mm.
Growing period: 150 days.
Plot size: 4 m^2.

Sowing date: 5th to 7th March 1990.
Seed rate: 250 seeds/m^2.
Harvesting date: 4 - 6th August 1990.

Table 2.3.1-4. Experimental details: ryegrass/clover mixture in field experiment (F1EX90).

Crop growth stage		Fertilizer treatment (N levels)						
		1	2	3	4	5	6	7
5th Apr. 1990	(nitram g/plot)	0	9	18	27	36	45	54
After 1st cut	(nitram g/plot)	0	24	48	72	96	120	144
Total	(nitram g/plot)	0	33	66	99	132	165	198
Total	(kg N/ha)	0	28	57	85	114	142	171

Varieties and seed rates: see Table 2.2.1-4.
Sowing date see Table 2.2.1-4.
Plot size: 4 m^2.
Harvesting date: first cut on 21st to 23rd June 1990.
second cut on 2nd to 3rd September 1990.

Experimental procedures

Before sowing barley, lupin and rape in early March 1990, the experimental area (with the exception of the herbage plots) was sprayed with glyphosate herbicide (commercial name: Round-up, 100 ml in 20 litres water over 500 square metres) and after a week the soil was turned over to a depth of 20 cm with a fork and levelled with a rake, in all plots except those containing the ryegrass/clover mixture. Weeds on pathways were controlled by herbicide (Round-up), whilst weeds within the plots were carefully pulled out manually.

Harvesting

The ryegrass/clover mixture (21 plots) was harvested over an area of 1 square metre and fresh weights taken. Subsamples of about 500 g were then taken from each plot and dried at 100^0 C for 18 hours for estimation of water content and a further 50 g sample from each plot dried at 65^0 C for two days for subsequent nitrogen assessment.

The total biomass of barley, rape and lupin was harvested at the end of the experiment from the central one square metre of each plot. Seeds were, then, manually separated from biomass. Straw (stems and leaves) and seeds were dried at 100^0 C for 18 hours to estimate dry matter.

Because of a severe drought in the growing season, which resulted in poor yields, no subsamples were taken for subsequent nitrogen assessment for barley, lupin and rape.

2.3.2 Results of field experiment (F1EX90)

2.3.2.1 Rainfall during the period of the experiment

The cumulative rainfall from 1st March 1990 to 20th July was only 125.5 mm, which was 54.7% of the previous year (229.5 mm) over the same period. The total rainfall in March 1990 was only 9.6 mm, followed by 25.9 mm and 17.4 mm in April and May 1990 respectively. The weather record at the Ness Botanic Gardens showed that the rainfall of 29.7 mm, received in the period 24th - 28th February 1990, have provided adequate soil moisture for germination of March sown seed but little support the subsequent growth. The annual total rainfall of 644 mm (from 1st January 1990 to 31st December 1990) was less than the minimum yearly rainfall of 650.2 mm over the 73-year period from 1879 to 1943.

This severe drought resulted in very poor growth of the spring sown crops and some plots, in fact, only had a few plants. In contrast, the ryegrass/clover mixture, which was continued from the previous year, continued to grow.

2.3.2.2 Biomass and economic yields

Statistical analysis showed that biomass and seed (economic) yields of spring sown barley, lupin, rape and the ryegrass/clover mixture differed significantly from one another ($P < 0.01$) (Table 2.3.2-1 and Table 2.3.2-2). There was a highly significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass and economic yields of the crops in general, and nitrogen fertilizer had significant differential effects (interactions) on the biomass and economic yields of the four crops ($P < 0.01$), No differences amongst blocks were apparent ($p > 0.05$) both for biomass and economic yield.

Table 2.3.2-1. Analysis of variance of biomass of spring sown barley, lupin, rape and ryegrass/clover mixture in the field experiment (F1EX90).

Source	DF	Sum of squares	F	P_{HO}
Block	2	344333	1.07	0.3502
Crop	3	1648442820	3414.51	0.0001
Fertilizer	6	45040629	46.65	0.0001
Crop*fertilizer	18	113060105	39.03	0.0001
Error	54	8689967		
Total	83	1815577855		

Table 2.3.2-2. Analysis of variance of economic yields of spring sown barley, lupin, rape and ryegrass/clover mixture in the field experiment (F1EX90).

Source	DF	Sum of squares	F	P_{HO}
Block	2	454073	1.80	0.1748
Crop	3	1754042222	4640.21	0.0001
Fertilizer	6	40209992	53.19	0.0001
Crop*fertilizer	18	117054328	51.61	0.0001
Error	54	6804165		
Total	83	1918564780		

Comparison of mean yields, pooling over fertilizer application, suggests that the yields of spring sown barley, lupin and rape were statistically similar and as a group differed from the much higher yield of the ryegrass/clover mixture (Fig 2.3.2-1).

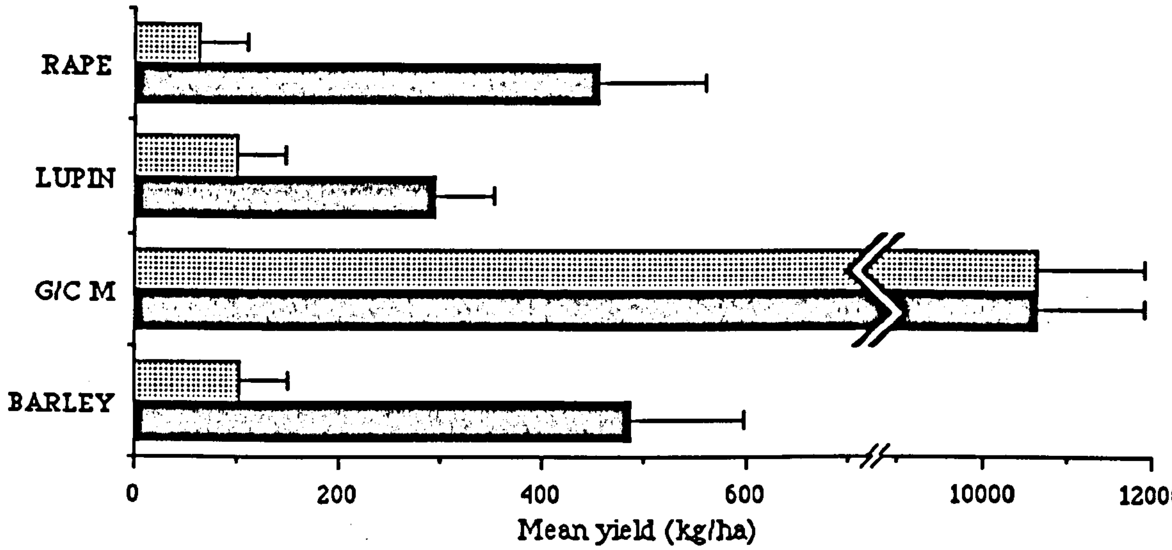

Fig 2.3.2-1. Comparison of yields of barley, lupin, rape and ryegrass/clover mixture, using pooled data over N fertilizer application (experiment F1EX90). Confidence limits are standard errors of the mean.

G/C M = ryegrass/clover mixture

■ Biomass, LSD = 248 kg/ha ▦ Economic yield, LSD = 220 kg/ha

Fig 2.3.2-1 clearly indicates that the yield of the ryegrass/clover mixture was 21.9 time higher than that of barley, 40.9 times greater than that of lupin and 24.5 times higher that that of rape. Its economic yield was 104 times higher than that of barley, 121 times greater than that of lupin and 174 times higher than that of rape.

2.3.2.3 Yield responses to nitrogen fertilizer

Although scatter graphs showed that the yields of barley, lupin and rape displayed some evidence of positive responses to nitrogen fertilizer, correlation coefficients were not significant ($p > 0.05$) (Fig 2.3.2-2, Fig 2.3.2-3 and Fig 2.3.2-4). In contrast there was a clear response to nitrogen by the ryegrass/clover mixture (Fig 2.3.2-5) and the contrasting response of the crops underlies the significance of the interaction detected by analysis of variance (Tables 2.3.2-1 & 2.3.2-2).

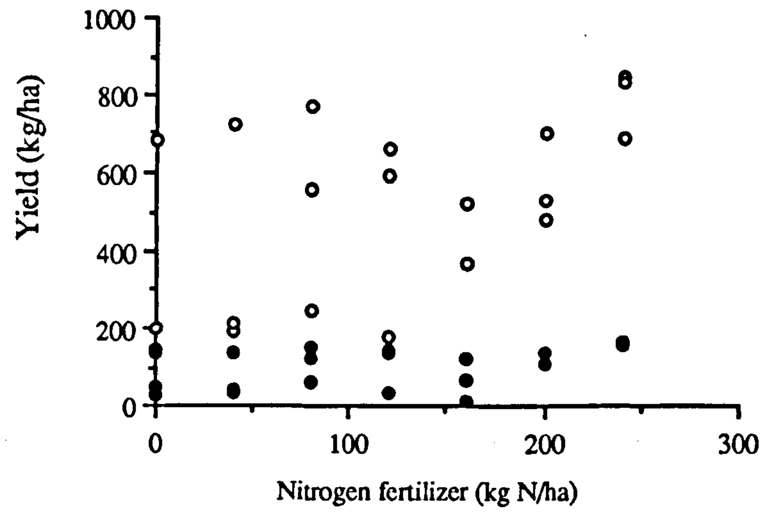

Fig 2.3.2-2. The yield of barley in response to nitrogen fertilizer in experiment (F1EX90).

o Biomass (r = 0.446) • Grain (r = 0.439)

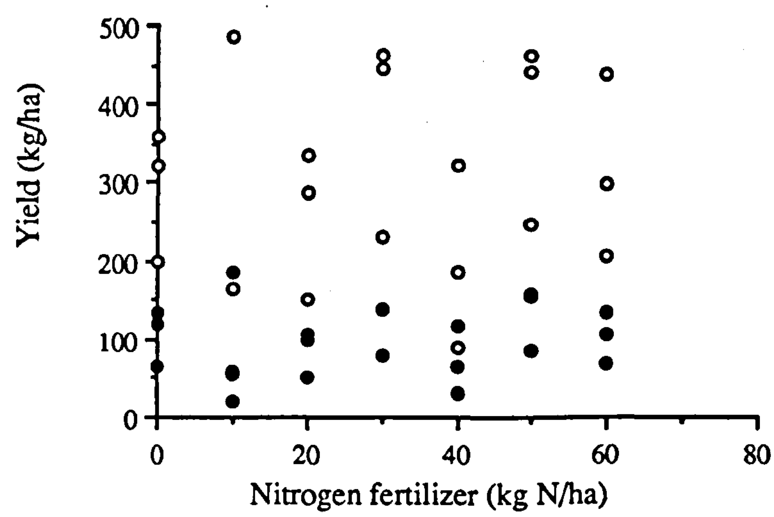

Fig 2.3.2-3. The yield of lupin in response to nitrogen fertilizer in experiment (F1EX90).

o Biomass (r = 0.167) • Lupin seed (r = 0.114)

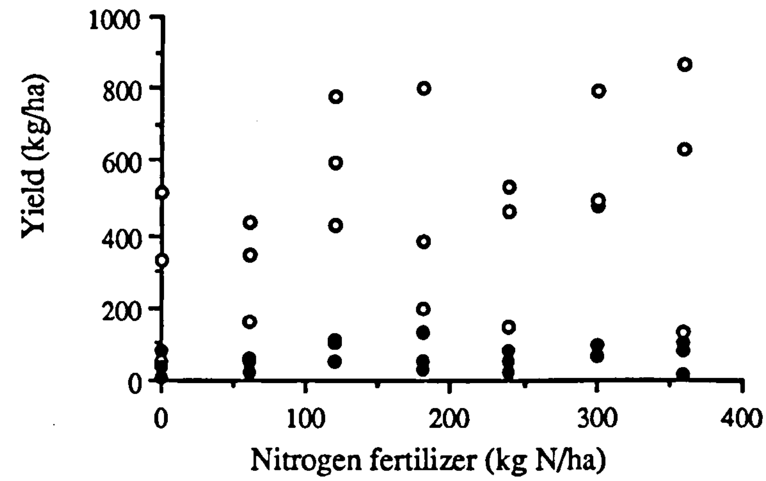

Fig 2.3.2-4. The yield of rape in response to nirogen fertilizer in experiment (F1EX90).

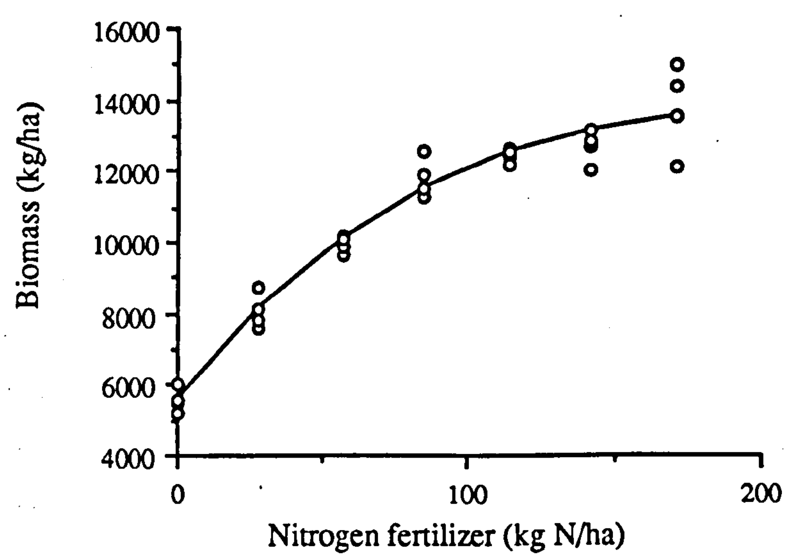

Fig 2.3.2-5. The biomass of ryegrass/clover mixture in response to nitrogen fertilizer in experiment (F1EX90).

The response to nitrogen fertilizer by the ryegrass/clover mixture is illustrated in Fig 2.3.2-5. Equation (10) provided a good fit to the data (R^2 = 0.9964) and the parameters and their standard errors are given in Table 2.3.2-3.

Table 2.3.2-3 Parameters and their standard errors after model fitting for ryegrass/clover mixture in experiment F1EX90 (SE = Standard error, G/C = ryegrass/clover mixture, yield in kg/ha).

Crops	b_0	b_0 SE	b_1	b_1 SE	b_2	b_2 SE	b_3	b_3 SE	R^2
G/C	5545	373	120.94	10.9	3.3e-3	0	1.3e-5	5.1e-6	0.9964

The yield response curve indicates a quadratic response over the nitrogen levels.

$$\text{Biomass} = \frac{5545 + 120.94N}{1 + 0.003316N + 0.000013N^2}$$

where biomass in kg/ha and N is nitrogen fertilizer in kg N/ha.

The maximum yield, estimated from the response curve at a nitrogen level of 214 kg N/ha, was calculated up to be 13634 kg/ha of dry matter. The economic response was similar to this being estimated at a nitrogen level of 200 kg N/ha and yielding 13619 kg/ha of dry matter. The yield of Y_{10} was 13414 kg/ha of dry matter, being 98.4% of the maximum yield. But the Y_{10} was achieved at a nitrogen level of 165 kg N/ha being 77.1% of the nitrogen level for the maximum yield.

2.3.2.4 Nitrogen content and crude protein yield

In this experiment, only dried ryegrass/clover was assessed for nitrogen content. Analysis of variance showed that nitrogen fertilizer did not affect the N content of the ryegrass/clover mixture significantly ($p > 0.05$) though a slight (but non-significant) positive relationship was evident (Fig 2.3.2-6).

The average nitrogen content (%) of the ryegrass/clover mixture in this experiment was 2.43% ± 0.98 suggesting a mean crude protein content of 15.2%. Crude protein yield (pooled data over seven levels of N fertilizer application) was calculated to be 1616 kg/ha.

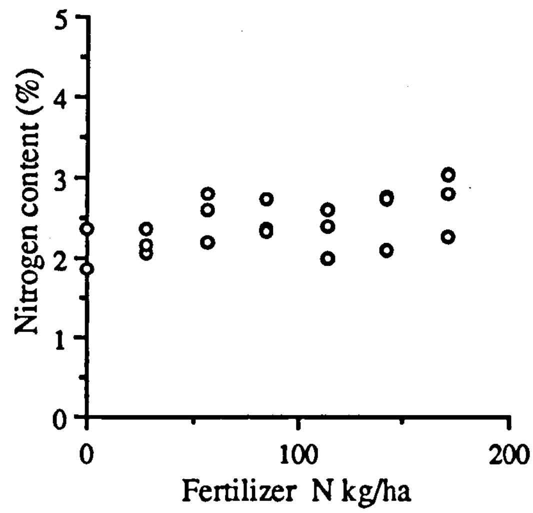

Fig 2.3.2-6. The influence of nitrogen fertilizer application rate on nitrogen content (%) of the herbage of the ryegrass/clover mixture in the field experiment (F1EX90). r = 0.457.

2.4 Discussion

(1) The yield performance of barley, lupin, rape and ryegrass/clover mixture in 1989 and 1990

In agriculture, the interpretation and comparison of yields is potentially complex since yielding ability involves several considerations when differing crops are involved. To the farmer it means economic return and high yields often mean successful management of an enterprise. To millions in the world, however, it provides a livelihood, a lifegiving support. An ecologist may interpret agriculture in terms of the relative flow of nutrient and energy among species and the interaction between organisms and their physical environment. Despite particular viewpoints, it is commonly agreed that high yield should be pursued to ensure sufficiency of food supply of high quality at a reasonable price and produced in such a way that resources are used efficiently and environmental protection is taken into consideration. Given this point of view, yield must be considered in relation to quantity and quality. Yield quality being assessed in this research was by means of crude protein content or crude protein produced per unit of area (crude protein yield) because in most cases the nutrient value of a food in the human diet or as a component of animal feed stuff is often limited by its protein content. Other comparisons of yield quality may be made also. The assessment of crude protein content (%) was achieved by multiplying nitrogen content (%) by a factor of 6.25. Although it may be argued that nitrogen contents of different proteins vary from 12 - 19% (Allen 1974) it is widely agreed that the results obtained by using 6.25 seem as satisfactory as those obtained by direct chemical methods (Helmprecht and Friedman 1977; Allen 1974).

Under MAFF recommended N fertilizer practice of 120 kg N/ha for barley, 300 kg N/ha for ryegrass/clover mixtures and 180 kg N/ha for rape in a season, the economic yields (given a 11% standard moisture for barley and ryegrass/clover and 9% standard moisture for rape seed) in 1989 were 4.15 ± 0.25 t/ha barley, 10.71 ± 0.40 t/ha dried ryegrass/clover biomass and 2.35 ± 0.29 t/ha rape. These are close to the average yields nationwide of recent years (MAFF, DAFS and MANI 1984, 1986a and 1986b; Morrison, Jackson and Sparrow 1980; NIAB 1989a). The lupin seed yield, 1.63 ± 0.13 t/ha at 50 kg N/ha in 1989, however, was much lower than the average yield of peas and field beans (dry matter 3.83 - 4.11 t/ha, NIAB 1989b).

In 1989, the total biomass yields of barley (dry matter 9.55 ± 0.37 with 120 kg N/ha) and rape (dry matter 8.83 ± 0.37 t/ha with 180 kg N/ha) were similar to that of the ryegrass/clover mixture (dry matter 9.53 ± 0.42 t/ha with 300 kg N/ha). In addition, the crude protein yields of the seed crops, barley (445 kg/ha), lupin (534 kg/ha) and rape (489 kg/ha) were very close. However, the average crude protein yield of the ryegrass/clover mixture (1400 kg/ha, pooled data over fertilizer application) was 2.6 - 3.1 times higher than those of barley, lupin and rape. This difference was due to both the higher yield of the ryegrass/clover mixture and its higher percent of crude protein content. The crude protein content (%) of the ryegrass/clover mixture (16.38% dry matter) was higher than that of barley seeds (12.69% dry matter).

The yield of barley, lupin and rape sown in 1990 was meagre due to the severe drought after sowing, which prevented crop establishment. In contrast, the ryegrass/clover mixture sustained yield throughout both seasons. This was probably due to the vigorous rooting system of the herbage mixture. The average total biomass (yearly dry matter 10.64 ± 2.87 t/ha, pooled data over fertilizer application) in 1990 was 24% higher than that observed in 1989 (8.55 ± 1.02 t/ha dry matter, averaged data over fertilizer application) though total rainfall (317.7 mm) within the growing season from March to October 1990 was lower than the 401.9 mm which occurred within the same period in 1989. This may be caused by firstly, the herbage mixture having experienced a period of establishment, growing slowly and not fully taking the advantage of available water (130.7 mm rainfall) in March and April 1989, secondly there being four cuttings in 1989 but only two cuttings in 1990. Another explanation may be due to the different amounts of fertilizer applied as well. Williams (1980) has shown that low cutting frequencies tend to increase yields but lower digestibility (NIAB 1989c).

The mean crude protein content (15.2% dry matter) of the ryegrass/clover mixture harvested in 1990 gave an estimated average protein yield of 1616 kg/ha, which was 28% higher than the protein yield in 1989 because of higher biomass production.

(2) Crop yield in response to N fertilizer in 1989 and 1990

The results of the two experiments in 1989 (F1EX89) and in 1990 (F1EX90) showed that barley, lupin, rape and the ryegrass/clover mixture responded differently to N fertilizer application. To interpret these differences, however, is complex since as with the comparison of yields of different crops the response to N fertilizer influenced by a number of interacting factors such as soil type, climate and crop husbandry. Although it is almost impossible to account for all factors which might have potential to affect the response of a crop to nitrogen fertilizer application, differences may be dominated by the biological nature of the crops when grown on the same soil type, under the same climate and the same type of farming management.

The demand for N fertilizer and the yield response was different amongst the four crops over the two seasons and the unfortunate occurrence of the drought and the consequent changes in experimental design for the herbage mixture make between year comparisons difficult.

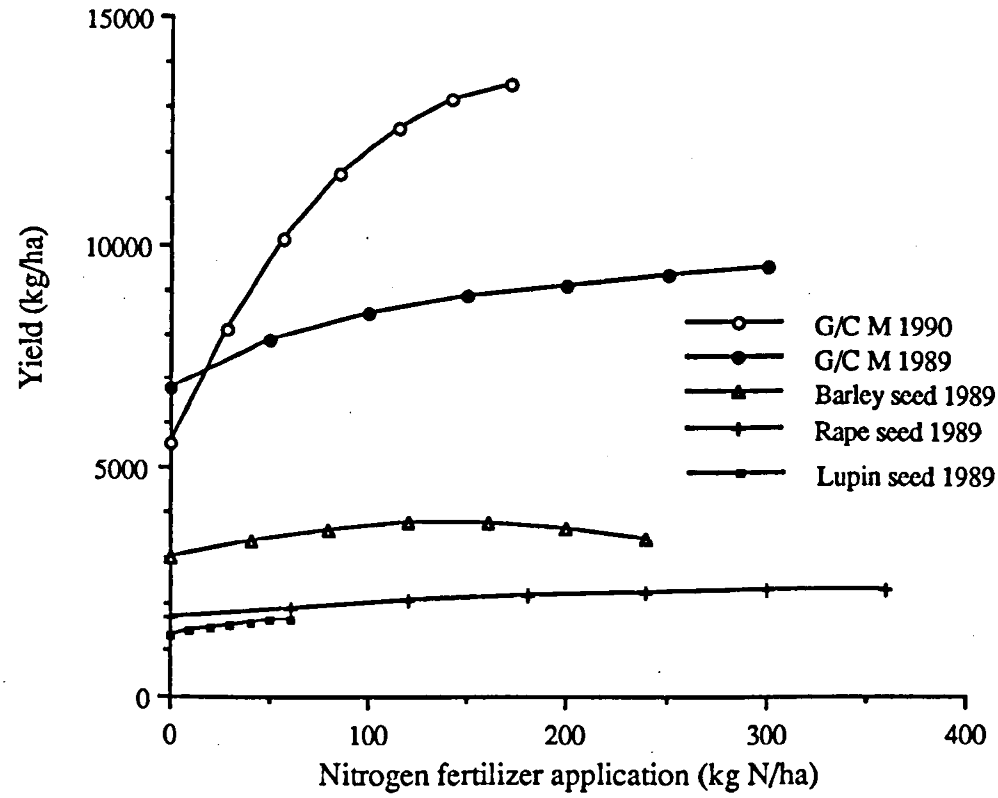

Fig 2.4-1. Comparison of crop yields in response to nitrogen fertilizer, using the estimates from the fitted response curves in the field experiments (F1EX89 & F1EX90).

In 1989, the maximum yield of barley obtained at the N fertilizer level of 136 kg N/ha and economic response at 112 kg N/ha considerably exceeded both the average maximum N (70 kg N/ha) and economic N (60 kg N/ha) dressing level obtained by Needham and Boyd (1976) in a comparative study of three barley cultivars over 4 cropping seasons. However they fell in the normal range of expected economic responses (from 0 to 150 kg N/ha) reported by Needham and Boyd (1976).

The economic N (210 kg/ha) dressing for rape in the experiment in 1989 was very close to the MAFF recommended level (188 kg N/ha).

The highest application level (300 kg N/ha fertilizer) for the ryegrass/clover mixture did not necessarily indicate the maximum yield attainable. Additional N may augment yield but increases may be small considering the yield response curve which shows an asymptotic response at high N. However, 300 kg N/ha agrees with the results of most of the experiments described by Morrison, Jackson and Sparrow (1980) as an optimal.

Amongst the four crops, the ryegrass/clover mixture exhibited the greatest nitrogen demand (the N level required for the economic response). This is to be expected since the crop had continuous vegetative growth. Lupin was the least N demanding, illustrative of the biological nature of a legume crop. In rape, however, twice as much nitrogen was needed for the same protein yield as in barley. One notable feature of rape was that a high proportion of nitrogen in leaves must have been left in the field as the leaves dropped before harvest. In rape, the lack of response to N fertilizer application may reflect a considerable difference in growth pattern and nitrogen utilization as compared to barley. At its very vigorous vegetative growing stage, rape may demand a larger supply of nitrogen than the other crops to yield the same dry matter. At later growing stages, the process of nitrogen transfer from leaves to stem and seeds might be not as efficient as barley, ryegrass/clover mixture and lupin. Evidence was found by Kullmann and Geisler (1988) that nitrogen translocation within rape differed between plants grown under low and high N supply. Little N was translocated from root, shoot and leaves of plants given high N, whereas in rape given low N a large part of the N accumulated in vegetative parts and pods was translocated into seed (Kullmann and Geisler 1988). The leaf dry matter, which dropped before the harvest, was not included in the biomass yield in the experiments reported here. Although the exact amount of leaf dry matter was unknown it may be up to 2 t/ha, comprising 16% of total dry weight of the plant at 8 - 10 weeks after germination (Munir 1982). Whether this part of the nitrogen component remained in the soil organic pool or was lost by leaching was unknown.

Literature (Langer and Liew 1973; Sylvester-Bradley and George 1987) has indicated a positive relationship between N grain content and total N fertilizer application. This relation was not observed in the experiments reported here because of differences in the timing of fertilizer application. High N content of grain is achieved by top dressing after ear emergence which was not applied in this experiment. The early application of N fertilizer has more effect on total yield than on N grain content (Langer and Liew 1973). The N contents in harvestable yields reported here reflect partitioning after fertilizer applications during vegetative growth.

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CHAPTER 3 COMPARATIVE YIELDS of SOME AUTUMN SOWN CROPS IN RESPONSE TO NITROGEN FERTILIZER

3.1 Introduction

The experiments described in Chapter 2 compared yields in responses to nitrogen fertilizer amongst spring sown crops. Crops sown in autumn usually show higher yields than those sown in spring primarily because autumn sown crops have a longer growth period to allow them to accumulate more dry matter and build up economic yield. Previous research has indicated that yield is closely related to available incident radiation and that light is a resource limiting yields in the U.K. (Scott and Allen 1978). Autumn sown crops provide an opportunity for farmers to attempt to maximize use of available radiation in yield production.

For example, the seed yield of autumn sown rape is usually 66% more than that of spring sown rape (NIAB 1989a) and the grain yield of autumn sown wheat is 49% more than that of spring sown wheat on average in field trails in the U.K. (NIAB 1989c).

Despite the apparent advantages of autumn sown crops, autumn sown lupin remains a doubtful practice because of stem disease (fusarium wilt) (Anon 1986). In practice, a spring sown cultivar was included.

Since yield response curves of autumn sown cultivars may be different from those of spring sown ones for a number of reasons, presumably rainfall, incident radiation and temperature (Morrison, Jackson and Sparrow 1980; Cooke 1982) the main purpose of the work reported in this chapter therefore is to comparatively assess the yields of a range of autumn-sown crops, wheat, rape, a ryegrass/clover mixture in response to nitrogen fertilizer application over 1989 - 1990 and wheat, rape, the ryegrass/clover mixture and spring sown lupin in response to N fertilizer over 1990 - 1991.

3.2 Comparison of yields in response to nitrogen fertilizer amongst wheat, rape and a ryegrass/clover mixture in field experiment (F2EX90)

In this experiment, there were two autumn-sown cultivars of rape used. One cultivar was Tapidor and another cultivar was Cobra. The main differences between the two cultivars were that Cobra grows taller and gives higher yield but has a higher glucosinolate content than Tapidor.

3.2.1 Materials and Methods

Experiment design

A field experiment, coded F2EX90, was conducted to examine the yield of autumn sown wheat (cultivar: AVALON), two varieties of oilseed rape (cultivars: Tapidor and Cobra) and a ryegrass (*L. perenne*, cultivar: Antrim and *L. multiflorum*, cultivar: RVP) / white clover (*T. repens*, cultivar: Grasslands Huia) mixture at each of seven levels of nitrogen application , giving 28 treatments.

The experimental design was a randomized complete block (3 blocks) with three replicates, giving a total number of eighty four plots. The experiment was conducted over the period of October 1989 to July 1990 for wheat and rape and extended until October 1990 for the ryegrass/clover mixture. Details are given in Table 3.2.1-1 to Table 3.2.1-3.

Four m^2 plots with 0.5 metre guard areas were initially established with a central 1 m^2 area for harvesting. Plots were separated from one another by 1 m paths to minimize the effects of nitrogen movement through surface water runoff and soil drainage.

The crops were grown over seven levels of nitrogen fertilizer application with different increments for each crop. The highest level for each was determined by the individual requirements of the crops examined. These upper limits were chosen to exceed the normal fertilizer recommendation for the crops (MAFF 1983) and the lowest application treatment, no nitrogen fertilizer, was common to all. The experiments described in Chapter 2 confirmed that seven levels of nitrogen fertilizer application were adequate for statistical purpose.

To ensure sufficient supplies of phosphate and potassium, 276 grammes of ICI No 12 fertilizer (N, P, K, = 0, 8.73%, 26.56%) were uniformly applied to each plot just before seed sowing by raking fertilizer into the top 15 cm of the soil. This addition is equivalent to 60 kg/ha of P and 183 kg/ha of K. The N fertilizer used in the experiment was 'NITRAM' (NH_4NO_3, 34.5% N).

Specific experimental details for each crop are summarized in the following tables.

Table 3.2.1-1. Experimental details: winter wheat in field experiment F2EX90. (GS = Feekes' growth stage).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	10.7	21.5	32.2	43.0	53.7	64.5
GS 2 - 3 (nitram g/plot)	0	21.5	43.0	64.5	86.0	108	129
GS 5 - 6 (nitram g/plot)	0	25.1	50.1	75.2	100	125	150
GS 8 - 9 (nitram g/plot)	0	12.3	24.5	36.8	49.0	61.2	73.5
Total (nitram g/plot)	0	69.6	139	209	278	348	417
Total (kg N/ha)	0	60	120	180	240	300	360

Variety: AVALON.
Sowing depth: 25 - 35 mm.
Harvesting date: 26th July 1990.
Sowing date: 15th Oct 1989.
Seed rate: 390 seeds/m^2.
Growing period: 284 days.

Table 3.2.1-2. Experimental details: winter oilseed rape in field experiment (F2EX90).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	14.3	28.7	43.0	57.3	71.6	86.0
First true leaf (nitram g/plot)	0	28.7	57.3	86.0	115	143	172
Vegetative growth* (nitram g/plot)	0	33.4	66.9	100	134	167	201
Flowering (nitram g/plot)	0	16.4	32.6	49.0	65.4	81.7	98.0
Total (nitram g/plot)	0	93	186	278	371	464	557
Total (kg N/ha)	0	80	160	240	320	400	480

Variety 1: Tapidor.
Sowing date: 15th Oct 1989.
Seed rate: 250 seeds/m^2.
Growing period: 291 days.

Variety 2: Cobra.
Sowing depth: 15 - 20 mm.
Harvesting date: 2th August 1990.

* 5 months from sowing (March).

Table 3.2.1-3. Experimental details: ryegrass/clover mixture in field experiment (F2EX90).

Date of application	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
15/10/89 (nitram g/plot)	0	18	36	54	72	90	108
18/3/90 (nitram g/plot)	0	5.7	11	17	23	28	34
7/4/90 (nitram g/plot)	0	5.7	11.5	17.0	22.7	28.4	34
13/6/90 (nitram g/plot)	0	24	47.8	71.6	95.5	119	143
31/8/90 (nitram g/plot)	0	4.8	9.5	14.6	19.4	24.1	29.0
Total (nitram g/plot)	0	58	116	174	232	290	348
Total (kg N/ha)	0	50	100	150	200	250	300

Sowing date	15/10/89.		
Varieties:	Antrim	RVP	Grasslands Huia.
Seed rate (g/plot)	12	12	10
Seed (%) in mixture	23%	23%	44%
Cuttings	1st	2nd	3rd
Date:	7/6/90	28/8/90	13/10/90

Experiment procedures

The experimental site had previously been cropped with winter wheat for four successive seasons.

Before crop sowing in mid October 1989, the experimental area was sprayed with the herbicide glyphosate (commercial name: Round-up, 100 ml in 20 litres water for 500 square metres) and, after a week, the soil was ploughed and levelled with a disc harrow. Subsequent weed control on pathways was achieved by herbicide application (Round-up), weeds in the plots being carefully pulled out manually.

Harvesting

All crops were harvested from the central 1 square metre of each plot. In harvesting the ryegrass/clover mixture, the total biomass was estimated for each plot, and then, a 100 g sample was taken for each plot and dried at 100^0 C for 18 hours for estimation of dry matter and a further 50 g sample of each plot dried at 65^0 C for two days, for subsequent nitrogen assessment.

For winter wheat, whole plant subsamples of 400 g were taken from each plot and dried at 100° C for 18 hours to estimate dry matter. From each subsample, grain was separated from biomass and the harvest index (grain weight divided by weight of total biomass) calculated, by which grain yield was estimated. Straw and grain of winter wheat of each plot were also sampled and dried at 65^0 C for subsequent nitrogen assessment.

In harvesting oilseed rape, all plants from the central 1 m^2 of each plot were air-dried in a polythene tunnel after having been cut at ground level. Seeds were then separated from plant material and the biomass of air-dried stem and seed estimated separately. Subsamples of about 100 g of stem and 20 g of seed of each plot were taken and dried at 100^0 C for 18 hours for estimation of dry matter. Further subsamples of stem and seed of each plot (10 g) were also taken and dried at 65^0 C for two days for subsequent nitrogen assessment.

Dried samples for nitrogen assessment were stored at laboratory temperature until analysis.

Soil analysis

Top soil (0 to 15 cm depth) was sampled on 5th October 1989 (before initial sowing) in each treatment plot for N assessment, and a pooled sample of soil on a block basis was taken for P and K assessment. The analytical methods used were as described in Chapter 2.

3.2.2 Results of field experiment (F2EX90)

3.2.2.1 Biomass and economic yields

Both the biomass and economic yield of the crops differed significantly ($p < 0.01$) from one other at harvest (Table 3.2.2-1 and Table 3.2.2-2). There was also a significant effect of level of nitrogen fertilizer on crop yield ($P < 0.01$). Analysis also showed that crops responded differently to nitrogen fertilizer ($P < 0.01$) in terms of biomass and economic yield. Differences amongst the blocks were not apparent ($p > 0.05$).

Table 3.2.2-1. Analysis of variance of biomass in field experiment (F2EX90).

Source	DF	Sum of squares	F	P_{HO}
Block	2	1481545	2.02	0.1427
Crop	3	97230499	88.34	0.0001
Fertilizer	6	340935455	154.89	0.0001
Crop*fertilizer	18	64924041	9.83	0.0001
Error	54	19810433		
Total	83	524381972		

Table 3.2.2-2. Analysis of variance of economic yield in field experiment (F2EX90).

Source	DF	Sum of squares	F	P_{HO}
Block	2	56568	0.52	0.5958
Crop	3	1181246170	7279.83	0.0001
Fertilizer	6	44385090	136.77	0.0001
Crop*fertilizer	18	15761377	16.19	0.0001
Error	54	2920731		
Total	83	1244369936		

Comparison of mean biomass yield, pooling over fertilizer applications, showed that the biomass of winter wheat (10738 kg/ha) and the ryegrass/clover mixture (10782 kg/ha) were statistically similar ($LSD_{0.05}$ = 375 kg/ha). The biomass of the ryegrass/clover mixture was 19.14% more than that of winter oilseed rape (cv: Cobra, 9050 kg/ha) and 29.92% higher than that of the short stem variety of winter oilseed rape (cv: Tapidor, 8299 kg/ha). The biomass of winter wheat was elevated over the rape varieties in approximately similar proportions. Of the two varieties of winter oilseed rape, the biomass of cv Cobra was 9.05% more than that of the short stem variety cv Tapidor.

Over all crops, the mean economic yield of the ryegrass/clover mixture was the highest (10782 kg/ha). It was about 2.4 times higher than that of winter wheat (4498 kg/ha), 6.18 times higher than that of cv Cobra (1744 kg/ha) and 7.4 times higher than that of cv Tapidor (1458 kg/ha) (Fig 3.2.2-1).

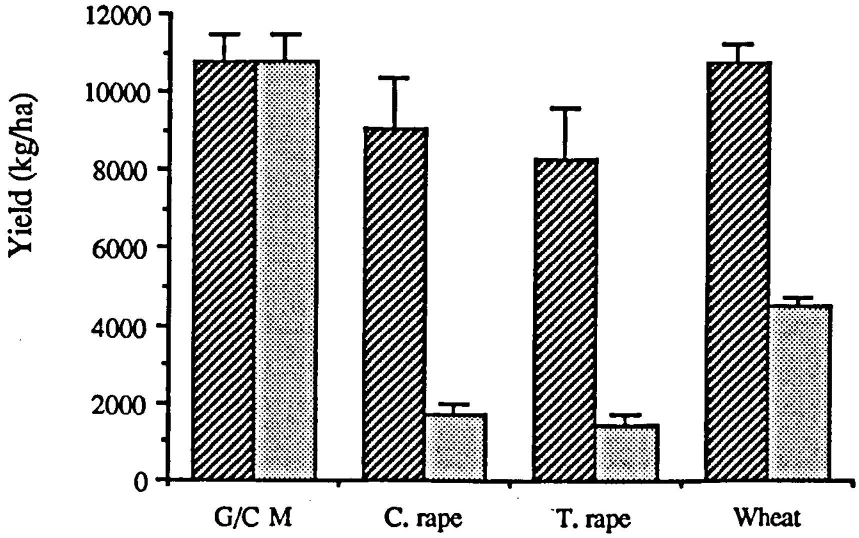

Fig 3.2.2-1. Comparison of yields of wheat, rape and ryegrass/clover mixture, using pooled data over N fertilizer application (experiment F2EX90). Confidence limits are standard errors of the mean.

(G/C M = ryegrass/clover mixture, C = Cobra, T = Tapidor)

▨ Biomass, LSD = 375 kg/ha ▩ Economic yield, LSD = 224 kg/ha

3.2.2.2 Yield responses to nitrogen fertilizer

The biomass and economic yield of all four crops showed a positive response to nitrogen fertilizer. Equation (10) (Chapter 1, section 1.5) was fitted to the data sets individually to model the yield-nitrogen relationships. Parameter estimates and their standard errors are given in Table 3.2.2-3.

Table 3.2.2-3. Parameters (standard errors) for equation (10) for each crop in experiment F2EX90 (SE = Standard error, C = Cobra, T = Tapidor, G/C M = ryegrass/clover mixture, B = biomass, kg/ha, E = economic yield, kg/ha).

Crops	b_0	b_0 SE	b_1	b_1 SE	b_2	b_2 SE	b_3	b_3 SE	R^2
Wheat B	8797	329	16.71	6.77	-9e-5	0	2.3e-6	2.5e-6	0.9973
Wheat E	3672	92.6	3.36	1.17	-1.1e-3	0	3.2e-6	6.5e-7	0.9986
C. Rape B	3218	343	89.85	29.7	5.82e-3	3.5e-3	1.0e-6	2.6e-6	0.9968
C. Rape E	655	83.0	11.22	4.52	2.07e-3	2.6e-3	3.2e-6	1.8e-6	0.9949
T. Rape B	3334	458	12.91	9.00	-2.5e-3	9.1e-4	5.0e-6	7.6e-7	0.9921
T. Rape E	520	90.1	5.48	1.24	-2.0e-4	0	3.0e-6	2.2e-6	0.9904
G/C M	8191	224	23.57	4.86	-2.1e-4	0	3.4e-6	1.6e-6	0.9988

The response of wheat to nitrogen

The yield-nitrogen relationship for winter wheat (cv Avalon) is illustrated in Fig 3.2.2-2.

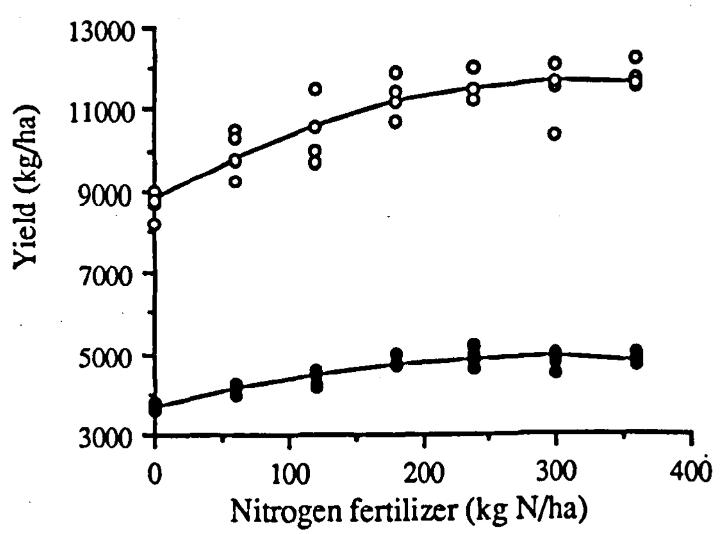

Fig 3.2.2-2. The yield of wheat in response to nitrogen fertilizer (experiment F2EX90).

o Biomass —o— Biomass fitted curve

• Seed yield —•— Seed yield fitted curve

Fitted curves for the biomass (kg/ha) and seed yield (kg/ha) are given by the equations

$$\text{Biomass} = \frac{8797 + 16.713N}{1 - 0.00009N + 0.0000023N^2}$$

$$\text{Seed yield} = \frac{3672.4 + 3.356N}{1 - 0.001105N + 0.000003N^2}$$

where N is nitrogen fertilizer in kg N/ha.

Estimated maximum grain yield of 4899 kg/ha was calculated to occur with a nitrogen application of 280 kg N/ha. The economic response, estimated at a nitrogen level of 219 kg N/ha, was 4835 kg/ha of dry grain, which is 98.7% of the maximum yield, but calculated with only 78.2% of maximum fertilizer level.

The response of the ryegrass/clover mixture to nitrogen

Fig 3.2.2-3 illustrates the relationship between total biomass and applied nitrogen for the ryegrass/clover mixture.

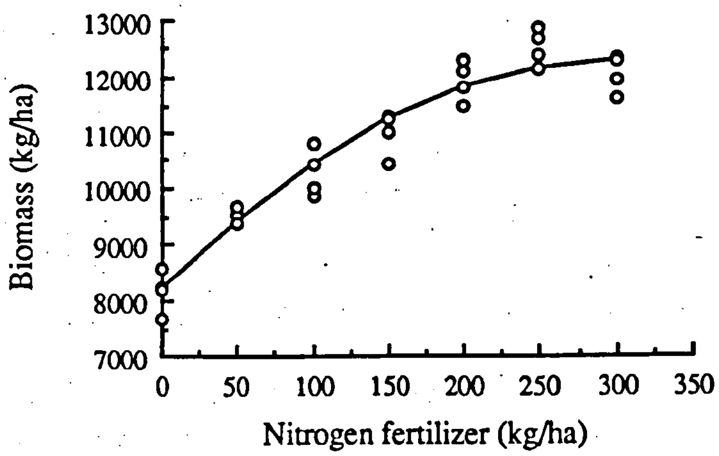

Fig 3.2.2-3. The biomass of ryegrass/clover mixture in response to nitrogen fertilizer (experiment F2EX90).

The yield response curve over the range of nitrogen applied was predominantly quadratic being given by the equation

$$\text{Biomass} = \frac{8191 + 23.569N}{1 - 0.00021N + 0.0000034N^2}$$

where N is nitrogen fertilizer in kg N/ha.

The maximum yield, from a nitrogen application of 313 kg N/ha, was found to be 12284 kg/ha of dry matter. The economic response, obtained at nitrogen level of 280 kg N/ha, was 12246 kg/ha of dry matter, being 99.7% of maximum yield. The Y_{10}, obtained at a level of 191 kg N/ha, was 11709 kg/ha dry matter, the N fertilizer level demand being 61% of the application for maximum yield.

The response of rape to nitrogen

The yield-nitrogen relationship of the rape cultivars is illustrated in Fig 3.2.2-4 and Fig 3.2.2-5. Yield responses were noticeably different, although maximum observed yields were similar.

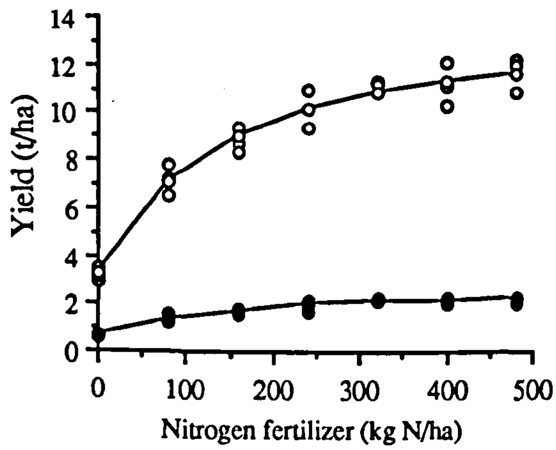

Fig 3.2.2-4. The yield of rape cv Cobra in response to nitrogen fertilizer (experiment F2EX90).

○ —○— Biomass fitted curve
● —●— Seed yield fitted curve

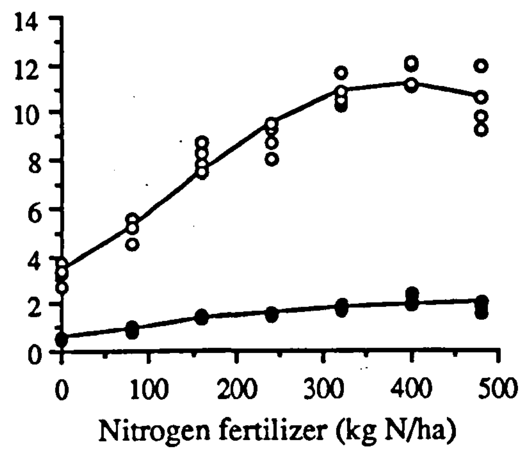

Fig 3.2.2-5. The yield of rape cv Tapidor in response to nitrogen fertilizer (experiment F2EX90).

○ —○— Biomass fitted curve
● —●— Seed yield fitted curve

$$BC = \frac{3218 + 89.852N}{1 + 0.005821N + 0.000001N^2}$$

$$BT = \frac{3334 + 12.912N}{1 - 0.002466N + 0.000005N^2}$$

$$SC = \frac{654.9 + 11.224N}{1 + 0.002073N + 0.0000032N^2}$$

$$ST = \frac{520.4 + 5.475N}{1 - 0.0002N + 0.000003N^2}$$

where BC is biomass (kg/ha) of cv Cobra; BT is biomass (kg/ha) of cv Tapidor; SC is seed yield (kg/ha) of cv Cobra; ST is seed yield (kg/ha) of cv Tapidor; N is nitrogen fertilizer (kg N/ha).

The maximum seed yield of cv Cobra was 2212 kg/ha at a fertilizer level of 469 Kg N/ha whilst cv Tapidor gave 1975 kg/ha with a nitrogen application of 495 kg N/ha. The economic response of cv Cobra was 2120 kg/ha at 310 kg N/ha and of cv Tapidor was 1891 kg/ha at 359 kg N/ha. The N fertilizer applications at the respective economic responses were 66% (Cobra) and 72.5% (Tapidor) of the applications for maximum yield.

3.2.2.3 Nitrogen content and crude protein yield

(1) Nitrogen content

There were significant differences ($p < 0.01$) amongst the nitrogen contents of the economic parts and straw (stem) of the four crops. Crops did not response in mean nitrogen content according to fertilizer level (Table 3.2.2-4) in a comparison of economic yield (grain and herbage) whilst nitrogen content of straw (stem) of wheat, rape and the ryegrass/clover mixture differed ($p < 0.05$) across nitrogen application levels (Table 3.2.2-4) and there was a significant crop nitrogen content and fertilizer treatment interaction.

Table 3.2.2-4. Analysis of variance of N content of the grain (or herbage) and straw of the four crops from the field experiment (F2EX90).

	Source	DF	Sum of squares	F	P_{HO}
Grain or Herbage	Crop	3	197.58	500.19	0.0001
	Fertilizer	6	0.62	0.79	0.5821
	Crop*fertilizer	18	1.81	0.76	0.7323
	Block	2	0.07	0.27	0.7677
	Error	54	7.11		
	Total	83	207.19		
Straw	Crop	3	92.41	583.1	0.0001
	Fertilizer	6	0.74	2.32	0.0455
	Crop*fertilizer	18	1.77	1.87	0.0399
	Block	2	0.06	0.57	0.5697
	Error	54	2.85		
	Total	83	97.84		

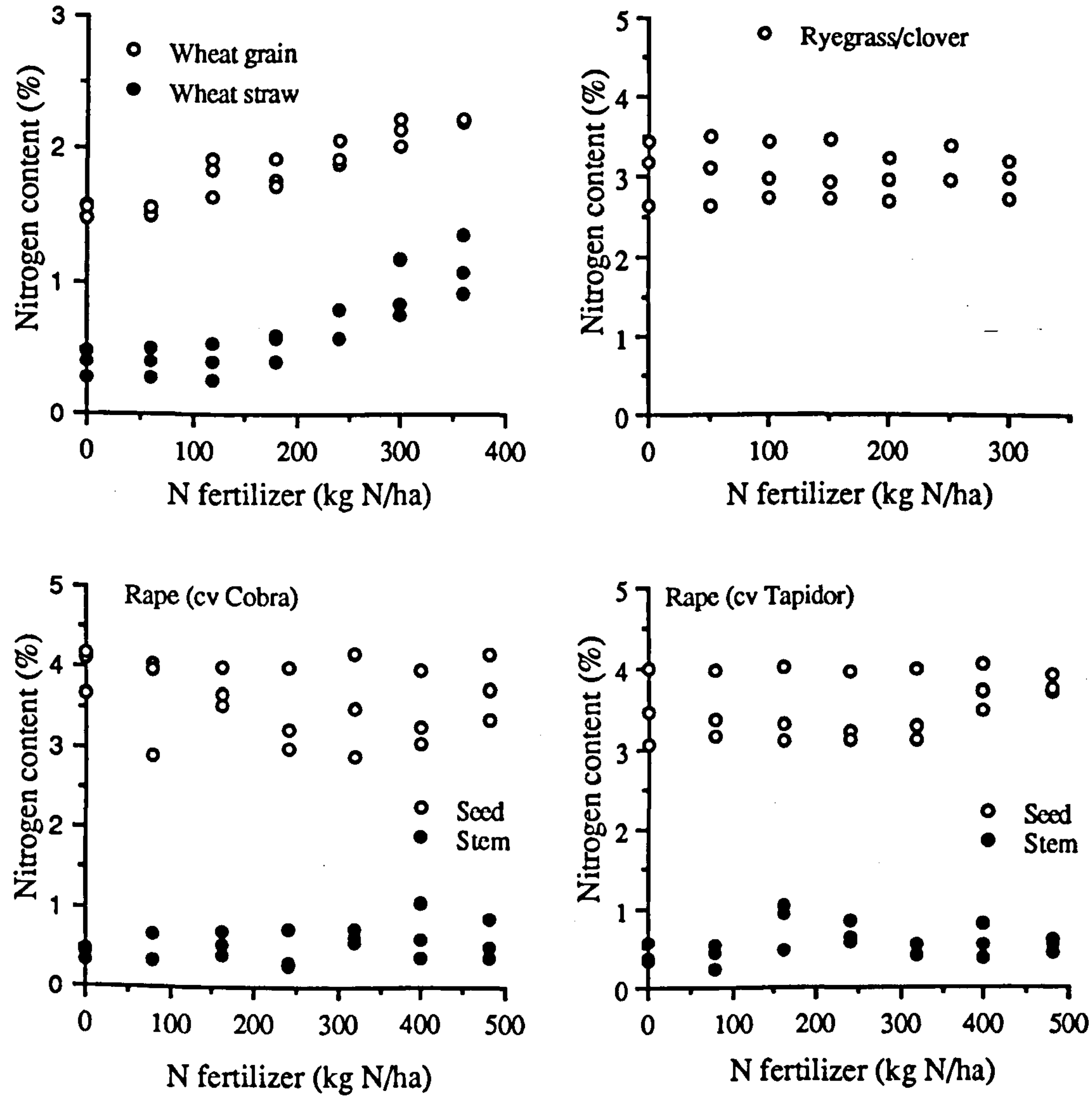

Fig. 3.2.2-5. The influence of nitrogen fertilizer application rate on nitrogen content (%) of the crop components in the field experiment (F2EX90).

Fig 3.2.2-5 illustrated that the nitrogen content of grain and straw of wheat was influenced by N fertilizer application whilst components of the other crops were not. This difference in crop performance explains the interaction between crops and fertilizer treatment indicated by analysis of variance.

The average nitrogen content, pooled data over N fertilizer application, is given by crop in Table 3.2.2-5.

Table 3.2.2-5. Average nitrogen content (mean % ± SEM) of the four crops, pooled data over nitrogen fertilizer application from the field experiment (F2EX90), (G/C M = Ryegrass/clover mixture).

	wheat	Rape cv Cobra	Rape cv Tapidor	G/C M
Economic part	1.85 ± 0.26	3.64 ± 0.44	3.55 ± 0.36	3.04 ± 0.29
Straw (stem)	0.64 ± 0.31	0.53 ± 0.21	0.55 ± 0.20	

(2) Crude protein yield

Average crude protein content (%) of economic parts of each crop was estimated by multiplying nitrogen content (%) by a factor of 6.25 (Helmprecht and Friedman 1977). The total crude protein yield was then calculated by multiplying economic yield by protein content (%) (Table 3.2.2-6).

Table 3.2.2-6. The average crude protein content (%) and crude protein yield (mean ± SEM) of the four crops. Pooled data over nitrogen fertilizer application from the field experiment (F2EX90). G/C M = Ryegrass/clover mixture. $LSD_{0.05}$ = 27 kg/ha.

	Wheat	Rape cv Cobra	Rape cv Tapidor	G/C M
Protein content (%)	11.56	22.75	22.19	19.00
Protein yield (kg/ha)	520 ± 12	397 ± 28	324 ± 27	2048 ± 63

The crude protein yield of the ryegrass/clover mixture was nearly 4 fold larger than that of wheat and 5 - 6 times higher than that of oil seed rape. Rape protein yields per ha were 62.3% (cv. Tapidor) and 76.3% (cv. Cobra) of wheat.

3.3 Comparison of yields in response to nitrogen fertilizer among wheat, rape, lupin and a ryegrass/clover mixture in field experiment (F2EX91)

A field experiment, F2EX91, was conducted from October 1990 to October 1991, to examine whether the yield response to nitrogen was stable in different years. To enable comparison of yield response in lupin over seasons one rape cultivar (Tapidor) was replaced by spring lupin (cv: Primorsk) since cv Tapidor gave a lower seed yield and the nitrogen fertilizer required to give the economic response was higher than that of Cobra.

3.3.1 Materials and Methods

Experiment design

Re-sowing of wheat, rape and lupin (with lupin replacing rape cv Tapidor) was carried out in the same plot so that the treatments and replicates were identical to those of experiment F2EX90. The plots of the ryegrass/clover mixture were maintained from the experiment F2EX90 to this experiment (F2EX91). The size of each plot was four square metres each with a central 1 square metre being designated for harvesting and half metre surroundings serving as guard areas. Phosphate and potassium were applied at the same level with the same method as in experiment F2EX90. The N fertilizer used in this experiment was also 'NITRAM' (NH_4NO_3, 34.5% N).

Specific experimental details for each crop are summarized in the following tables.

Table 3.3.1-1. Experimental details: winter wheat in the field experiment (F2EX91) (GS = Feekes' growth stage).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	10.7	21.5	32.2	43.0	53.7	64.5
GS 2 - 3 (nitram g/plot)	0	21.5	43.0	64.5	86.0	106	129
GS 5 - 6 (nitram g/plot)	0	25.1	50.1	75.2	100	125	150
GS 8 - 9 (nitram g/plot)	0	12.3	24.5	36.8	49.0	61.2	73.5
Total (nitram g/plot)	0	69.6	139	209	278	348	417
Total (kg N/ha)	0	60	120	180	240	300	360

Variety: AVALON.
Sowing depth: 25 - 35 mm.
Harvesting date: 25th July 1991.
Seed rate: 390 seeds/m^2.
Sowing date: 2nd Oct 1990.
Growing period: 296 days.

Table 3.3.1-2. Experimental details: spring lupin in the field experiment (F2EX91).

Crop growth stage	Fertilizer treatment (N levels)						
	1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	6	12	18	24	30	36
First true leaf (nitram g/plot)	0	20	40	60	80	100	120
vegetative growth* (nitram g/plot)	0	20	41	61	82	102	122
Total (nitram g/plot)	0	46	93	139	186	232	278
Total (kg N/ha)	0	40	80	120	160	200	240

Variety: PRIMORSK.
Sowing depth: 25 - 35 mm.
Seed rate: 75 seeds/m^2.
Growing period: 160 days.
Sowing date: 21st March 1991.
Row spacing: 15 - 20 cm.
Harvesting date: 29th August 1991.

* Two months after sowing (May).

Table 3.3.1-3. Experimental details: winter oilseed rape in the field experiment (F2EX91).

Crop growth stage	Fertilizer treatment (N levels) 1	2	3	4	5	6	7
Seedbed (nitram g/plot)	0	14.3	28.7	43.0	57.3	71.6	86.0
First true leaf (nitram g/plot)	0	28.7	57.3	86.0	115	143	172
vegetative growth* (nitram g/plot)	0	33.4	66.9	100	134	167	201
Total (nitram g/plot)	0	76.4	153	229	306	282	459
Total (kg N/ha)	0	66	132	198	264	330	396

Variety: COBRA. Sowing date: 2nd Oct 1990.
Sowing depth: 15 - 20 mm. Seed rate: 250 seeds/m^2.
Harvesting date: No harvest, due to bird damage.

* Five months after sowing (March).

Table 3.3.1-4. Experimental details: ryegrass/clover mixture in the field experiment (F2EX91).

Date of application	Fertilizer treatment 1	2	3	4	5	6	7
13/10/1990 (nitram g/plot)	0	18	36	54	72	90	108
9/3/1991 (nitram g/plot)	0	18	36	54	72	90	108
25/4/1991 (nitram g/plot)	0	15	30	45	60	75	90
12/6/1991 (nitram g/plot)	0	25	50	75	100	125	150
11/7/1991 (nitram g/plot)	0	25	50	75	100	125	150
29/8/1991 (nitram g/plot)	0	15	30	45	60	75	90
Total (nitram g/plot)	0	116	232	348	464	580	696
Total (kg N/ha)	0	100	200	300	400	500	600

Varieties/mixture:	Antrim, RVP and Grasslands Huia.				
Sowing date:	15th October 1989.				
Cuts:	1st	2nd	3rd	4th	5th
Date/month	25/4	12/6	11/7	29/8	2/10

Experiment procedures

In this experiment wheat and rape were sown in early October in 1990 and lupin in March in 1991. The ryegrass/clover plots were carried forward from the previous experiment. Before sowing wheat, lupin and rape, the plots was treated with herbicide and prepared in the same way as described for experiment F2EX90. Soil was turned over by hand to a depth of 20 cm and levelled with a rake. Weed control was practiced as described earlier.

Harvesting

Harvesting procedures for crops in common followed those described earlier in this chapter.

Lupin was harvested over a central area of 1 square metre, entire plants including seeds from each plot being air-dried in a polythene tunnel after harvesting. Seeds were then separated from plants. Subsamples of air-dried stems and seeds were then taken and dried at 100^0 C (18 hours) for estimation of dry matter. Further samples of stems and seeds of each plot were also taken and dried at 65^0 C for subsequent nitrogen assessment.

The dried samples for nitrogen analysis were stored at laboratory temperature until analysis.

Soil analysis

Top soil (0 to 15 cm depth) was sampled for N assessment in each treatment after the experiment in 1991 on the day following crop harvest. From these soil samples taken for nitrogen assessment, pooled subsamples on a block basis were taken for subsequent P and K assessment. Analytical methods are described in Chapter 2.

3.3.2 Results of field experiment (F2EX91)

During the experiment, plots of oilseed rape were attacked by birds at a stage (January) when it was too late to re-sow the crop. Results presented here therefore relate to only the yields of wheat, lupin and the ryegrass/clover mixture.

3.3.2.1 Biomass and economic yields

The biomass and economic yield of wheat, lupin and the ryegrass/clover mixture differed very significantly ($p < 0.01$) from one other at harvest (Table 3.3.2-1). There was also a significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass and economic yield of the crops. Analysis of variance also indicated that crops responded differently to nitrogen application level ($P < 0.01$) both in terms of biomass and economic yield. No significant differences were detected amongst blocks.

Table 3.3.2-1. Analysis of variance of yield of autumn sown wheat, spring sown lupin and ryegrass/clover mixture in the field experiment (F2EX91).

Yield	Source	DF	Sum of squares	F	P_{HO}
Biomass	Block	2	3800526	1.64	0.2068
	Crop	2	670290292	290.11	0.0001
	Fertilizer	6	151009883	21.79	0.0001
	Crop*fertilizer	12	223153950	16.10	0.0001
	Error	40	46210029		
	Total	62	1094464681		
Yield	Source	DF	Sum of squares	F	P_{HO}
Economic yield	Block	2	1363378	2.33	0.1104
	Crop	2	766723474	1310.31	0.0001
	Fertilizer	6	38788305	22.10	0.0001
	Crop*fertilizer	12	39558362	11.29	0.0001
	Error	40	11702906		
	Total	62	858136424		

Pooling over the nitrogen fertilizer application, comparison of means showed that the biomass of winter wheat (16855 kg/ha) was 1.41 times higher than that of the ryegrass/clover mixture (11993 kg/ha) and 1.89 times greater than that of lupin (8934 kg/ha). The biomass yield of the ryegrass/clover mixture was 34% more than that of lupin.

Mean economic yield (pooling over the nitrogen fertilizer application) of the ryegrass/clover mixture (11993 kg/ha) exceeded that of winter wheat (7046 kg/ha) and was over three fold higher than that of lupin (3486 kg/ha). The seed yield of spring sown lupin was about half of that of the autumn sown wheat (Fig3.3.2-1).

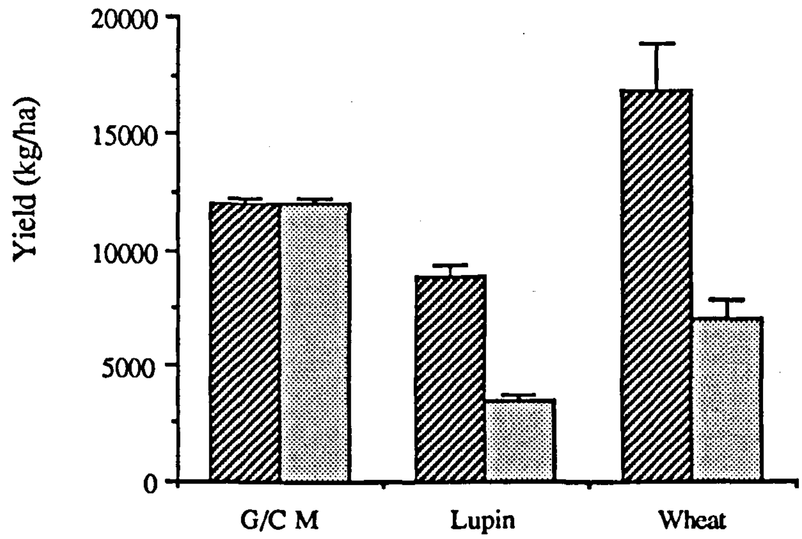

Fig 3.3.2-1. Comparison of yields of G/C M, Lupin and wheat, using pooled data over N fertilizer application (experiment F2EX91). Confidence limits are standard errors of the mean.

G/C M = ryegrass/clover mixture

Biomass, LSD = 670 kg/ha   Economic yield, LSD = 337 kg/ha

3.3.2.2 Yield responses to nitrogen fertilizer

The biomass and economic yield of the three crops responded positively to nitrogen fertilizer.

The estimated parameters (and their standard errors) of equation (10) are given in Table 3.3.2-2.

Table 3.3.2-2. Parameters and their standard errors after model fitting for each crop in the field experiment (F2EX91). SE = Standard error, G/C M = ryegrass/clover mixture, B = biomass, kg/ha, E = economic yield, kg/ha.

Crops	b_0	b_0 SE	b_1	b_1 SE	b_2	b_2 SE	b_3	b_3 SE	R^2
Wheat B	8838	767	73.16	17.1	0	0	5.5e-6	2.3e-6	0.9946
Wheat E	3389	356	35.12	7.4	0	0	6.8e-6	2.9e-6	0.9934
Lupin B	8374	433	26.05	11.2	0	0	1.4e-5	6.0e-6	0.9931
Lupin E	3208	165	11.89	7.1	0	0	1.6e-5	1.9e-5	0.9940
G/C M	10986	276	9.08	3.8	0	0	1.1e-6	8.2e-7	0.9985

The response of wheat to nitrogen

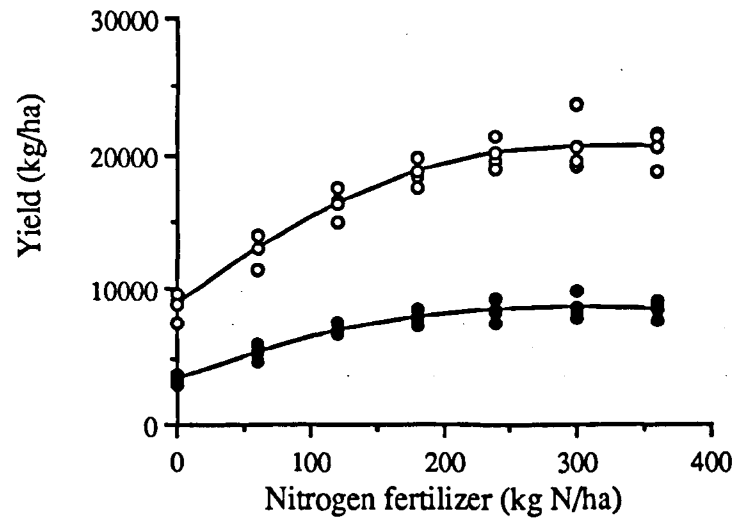

Fig 3.3.2-2. The yield of wheat in response to nitrogen fertilizer in the field experiment (F2EX91).

○ Biomass —○— Biomass fitted curve

● Seed yield —●— Seed yield fitted curve

Fitted curves describing the response to nitrogen fertilizer by wheat biomass (kg/ha) and seed (kg/ha) are given by the following equations

$$\text{Biomass} = \frac{8838 + 73.161N}{1 + 0.0000055N^2}$$

$$\text{Seed yield} = \frac{3389 + 35.117N}{1 + 0.00000676N^2}$$

where N is nitrogen fertilizer in kg N/ha, and yield are measured in kg/ha.

Maximum grain yield (8649 kg/ha) occurred at a nitrogen application of 300 kg N/ha. The economic response (8621 kg/ha) observed at nitrogen level of 273 kg N/ha, was close to the maximum yield observed, but only required 91% of the nitrogen fertilizer used to produce the maximum yield.

The response of the ryegrass/clover mixture to nitrogen

The yield-nitrogen relationship of the ryegrass/clover mixture is illustrated in Fig 3.3.2-3

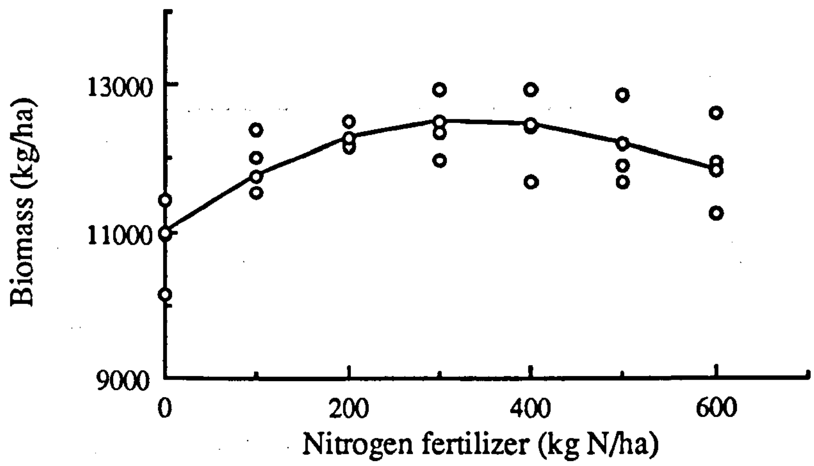

Fig 3.3.2-3. The yield of ryegrass/clover mixture in response to nitrogen fertilizer in the field experiment (F2EX91).

o Biomass —o— Biomass fitted curve

There was a clearly pronounced optimal level of fertilizer for maximum biomass production as indicated by the curve represented by the equation

$$\text{Biomass} = \frac{10986 + 9.078N}{1 + 0.000001086N^2}$$

where biomass is in kg/ha and N is nitrogen fertilizer in kg N/ha.

The yield response was noticeably parabolic and the maximum yield (12504 kg/ha) was produced at 334 kg N/ha. The economic response (12402 kg/ha) was obtained at a nitrogen level of 245 kg N/ha, 73.4% of the nitrogen required for the maximum yield. Y_{10} (11709 kg/ha) was observed at a nitrogen application of 191 kg N/ha, which was 61% of the nitrogen fertilizer for the maximum yield.

The response of lupin to nitrogen

The yield-nitrogen relationship of lupin is given in Fig 3.3.2-4 and indicates a much lower nitrogen requirement for maximum yield than was seen for the other crops.

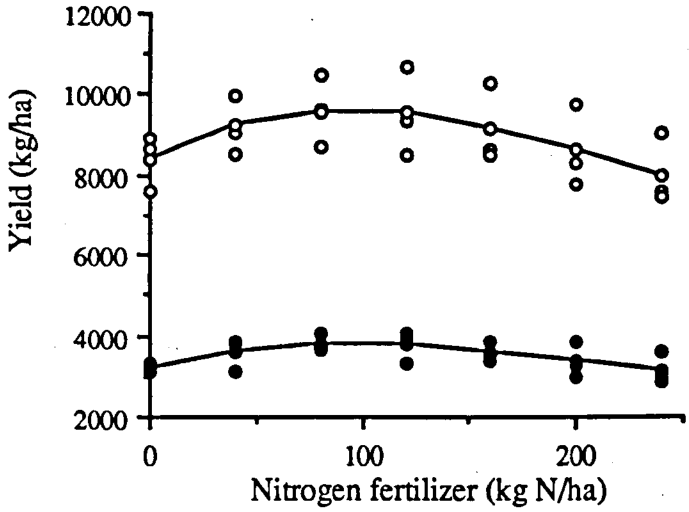

Fig 3.3.2-4. The yield of lupin in response to nitrogen fertilizer in experiment (F2EX91).

Fitted curves are as follows

$$\text{Biomass} = \frac{8374 + 26.053N}{1 + 0.0000143N^2}$$

and

$$\text{Seed yield} = \frac{3208 + 11.89N}{1 + 0.0000164N^2}$$

where N is nitrogen fertilizer in kg N/ha, and biomass and seed yield were measured in kg/ha.

The maximum seed yield (3778 kg/ha) was derived at a fertilizer level of 96 kg N/ha. This was close to the economic response (3769 kg/ha) at a nitrogen level of 83 kg N/ha. However, the requirement for nitrogen fertilizer was only 86.5% of the nitrogen level that gave maximum yield.

3.3.2.3 Nitrogen content and crude protein yield

(1) Nitrogen content

Crops displayed significantly different ($p < 0.01$) nitrogen contents in grain/herbage and straw. However, the nitrogen content of both economic parts and straw was independent of the level of nitrogen application (Table 3.3.2-4 and Fig 3.3.2-5).

Table 3.3.2-3. Analysis of variance of N content (%) of the grain (herbage) and straw of the three crops in the field experiment (F2EX91).

	Source	DF	Sum of squares	F	P_{HO}
Grain or Herbage	Crop	2	233.85	909.92	0.0001
	Fertilizer	6	1.37	1.78	0.1279
	Crop*fertilizer	12	0.95	0.61	0.8237
	Block	2	0.05	0.19	0.8178
	Error	40	5.14		
	Total	62	241.36		
Straw or Herbage	Crop	2	103.77	791.48	0.0001
	Fertilizer	6	0.82	2.08	0.0771
	Crop*fertilizer	12	0.76	0.97	0.8275
	Block	2	0.02	0.19	0.4963
	Error	40	2.62		
	Total	62	108.00		

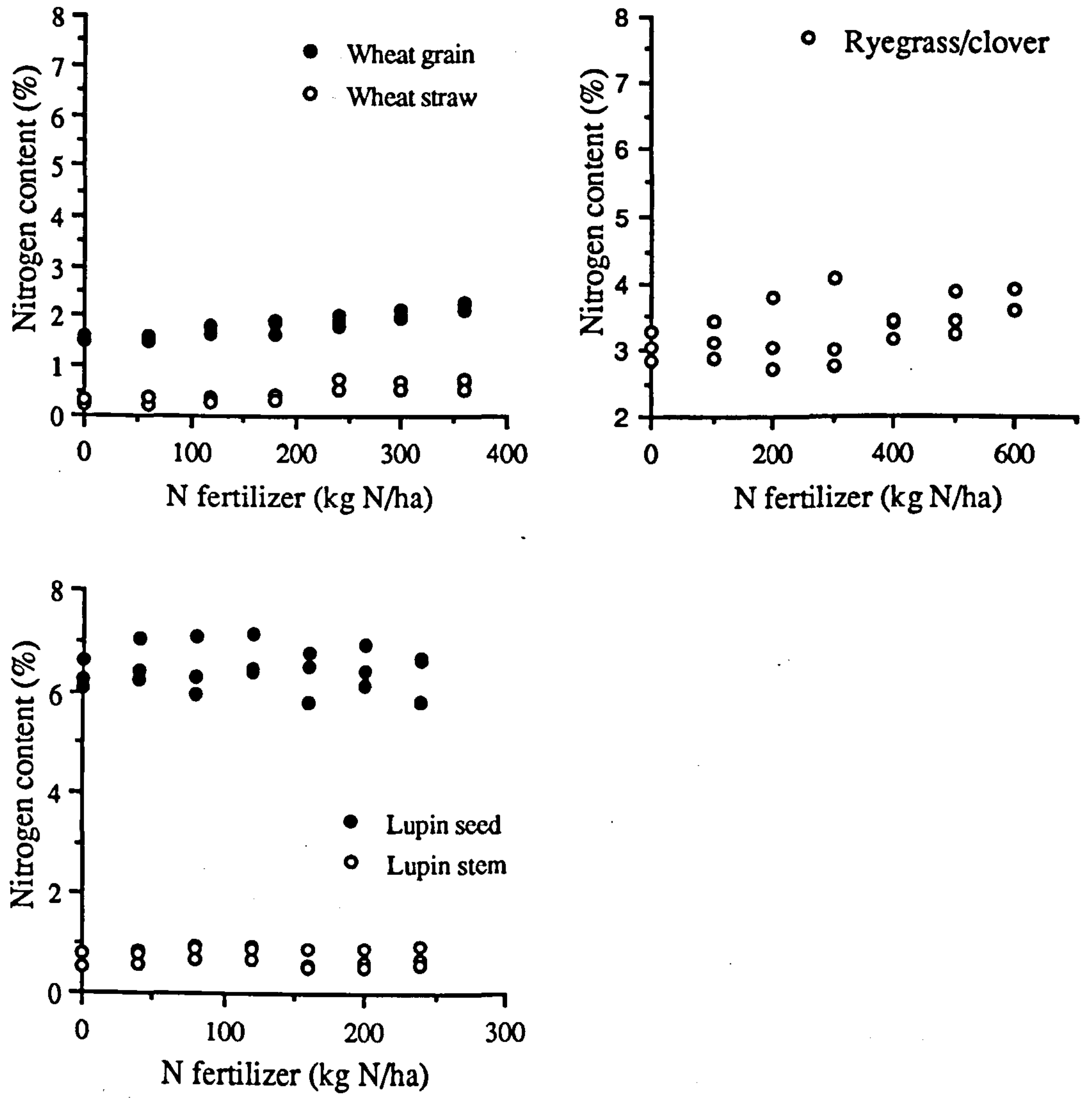

Fig. 3.3.2-5. The influence of nitrogen fertilizer application rate on nitrogen content (%) of the crop components in the experiment (F2EX91).

The average nitrogen content (%) (pooled over N fertilizer levels) of the economic yield and straw of the three crops is listed in Table 3.3.2-4. In rank order nitrogen contents were Lupin > the ryegrass/clover mixture > wheat.

Table 3.3.2-4. Average nitrogen content (%) (mean ± SEM) of the three crops, pooled data over nitrogen fertilizer levels in the field experiment (F2EX91). G/C M = Ryegrass/clover mixture.

	wheat	Lupin	G/C M
Economic parts	1.84 ± 0.25	6.46 ± 0.40	3.32 ± 0.39
Straw (stem)	0.46 ± 0.18	0.76 ± 0.16	

(2) Crude protein yield

The crude protein yield of the three crops was calculated from the seed (or herbage) yield multiplying by its protein content (%) (Table 3.3.2-5).

Table 3.3.2-5. Average crude protein content (%) and protein yield (mean ± SEM) of the three crops, pooled data over nitrogen fertilizer application, in the field experiment (F2EX91). G/C M = Ryegrass/clover mixture. $LSD_{0.05}$ = 70 kg/ha.

	Wheat	Lupin	G/C M
Protein content (%)	11.50	40.38	20.75
Protein yield (kg/ha)	810 ± 50	1408 ± 32	2489 ± 31

Rank order of protein yield differed as a consequence of absolute yield and indicated that the ryegrass/clover mixture outperformed lupin, the lowest protein yield being given by wheat.

3.3.2.4 Rainfall

Over the two cropping seasons 1989 - 90 and 1990 - 91 total rainfall and its seasonal distribution were conspicuously different and in consequence yields were substantially effected. In 1990, monthly rainfall receipts were 9.6 mm in March, 25.9 mm in April and 17.4 in May and the total rainfall from March to August was 169.9 mm. This total was 82.2% of the precipitation which occurred over the same period in

1991. By contrast there were only two relatively dry months in 1991, in May (10.8 mm) and August (15.3 mm) and the total rainfall from March to August was 206.6 mm. Rainfall was higher and more evenly distributed in March, April, June and July of 1991, monthly receipts ranging from 31.9 mm to 53.7 mm. More detailed information on the monthly distribution of rainfall is given in Chapter 5.

3.4 Discussion

(1) Between year comparison of crop yield

The average wheat grain yield (4498 kg/ha, pooled over N fertilizer application) in 1989 - 90 was 64% of the mean yield (7046 kg/ha, pooled over N fertilizer application) of that recorded in 1990 - 91. This yield decline is highly likely to have been the direct result of water shortage since it occurred over several growth stages when yield components were laid down (tillering, flowering, seed set).

In the dry spring of 1990, the rape seed yield (Tapidor 1.46 t/ha and Cobra 1.74 t/ha) was less than half of the average yield (3.45 to 3.74 t/ha) listed in the variety recommendation list (NIAB 1989a) and only 50 - 60% of the average yield (2.95 t/ha) nationwide in 1980 (Johnson 1981). Unfortunately, no data were obtained for the rape crop in 1991 due to plot damage by birds. Whilst it is difficult to explain the selective removal of the rape when the wheat crop was also quite young, the loss was probably due to migrant birds, possibly geese, over wintering on the river Dee estuary which was close to the experimental site.

Average herbage yields from the ryegrass/clover mixture in experiments (F2EX90 and F2EX91) were in the range (6 - 15 t dry matter/ha) of the mean yields reported by Morrison, Jackson and Sparrow (1980). The pooled average yield (10782 kg/ha) of the herbage mixture in 1990 was only 11% lower than that harvested in 1991 (11993 kg/ha). The two relatively dry months of May (10.8 mm) and August (15.3 mm) in 1991 may reduce the herbage yield of the mixture in the year. The total amount of precipitation from March to September in the two years, 1990 and 1991, was very similar, 239 mm and 232 mm respectively.

The average lupin seed yield (3486 kg/ha), pooled over fertilizer was 9 to 15% lower than the normal yield of peas and field beans (3.83 to 4.11.t/ha) in the U.K. (NIAB 1989b). Its average crude protein yield of 1408 kg/ha was higher than that of peas and field beans (940 to 1200 kg/ha) (NIAB 1989b; Monti 1983; Sator 1983).

The comparative yield performances of the winter sown crops showed the same ranking as those among the spring sown crops described in Chapter 2, except that the rape gave the lowest yield in this experiment. The average yields of the ryegrass/clover mixture were the highest of all crops in terms of both dry matter and crude protein yield/ha. The crude protein yield of the ryegrass/clover mixture was 4 times and 3 times higher than that of wheat in 1989 - 90 and 1990 - 91 respectively though the total biomass (grain plus straw) of wheat was almost the same as and much greater than that of the ryegrass/clover mixture over the seasons respectively.

Using the published data (average 23% protein content) of Swaminathan (1983) and annual summaries of rape seed yield (3 to 3.8 t/ha) for the U.K. (MAFF, DAFS and MANI 1982, 1983 and 1984) it can be calculated that rape may produce as much as or more protein per ha than wheat having an average grain yield of 5 - 6 t/ha with an average protein content of 12% (MAFF, DAFS and MANI 1982, 1983 and 1984). In this experiment in 1990, the average crude protein yield of oil seed rape (361 kg/ha, pooled over N fertilizer application and cultivars) was only 69% that of wheat, which may reflect the poor performance of rape when water is limited.

With high seed protein content, the average protein yield (1408 kg/ha) of lupin was 1.73 times higher than that of wheat.

(2) Crop yield in responses to N fertilizer in the cropping seasons 1980 - 90 and 1990 - 91

Fig 3.4-1 illustrates the yield responses to nitrogen application described by equation (10) over the two cropping seasons 1989 - 90 and 1990 - 1991. The response curve for lupin has been superimposed from Fig 2.4-1 for comparative purpose. This graph clearly indicates the magnitude of the seasonal influence on both maximum grain/herbage yields and the response to nitrogen application by the crop considered.

The results from the experiments F2EX90 and F2EX91 indicated that wheat grain yields changed considerably between seasons in terms of maximum response (Y_m) and economic response (Y_e).

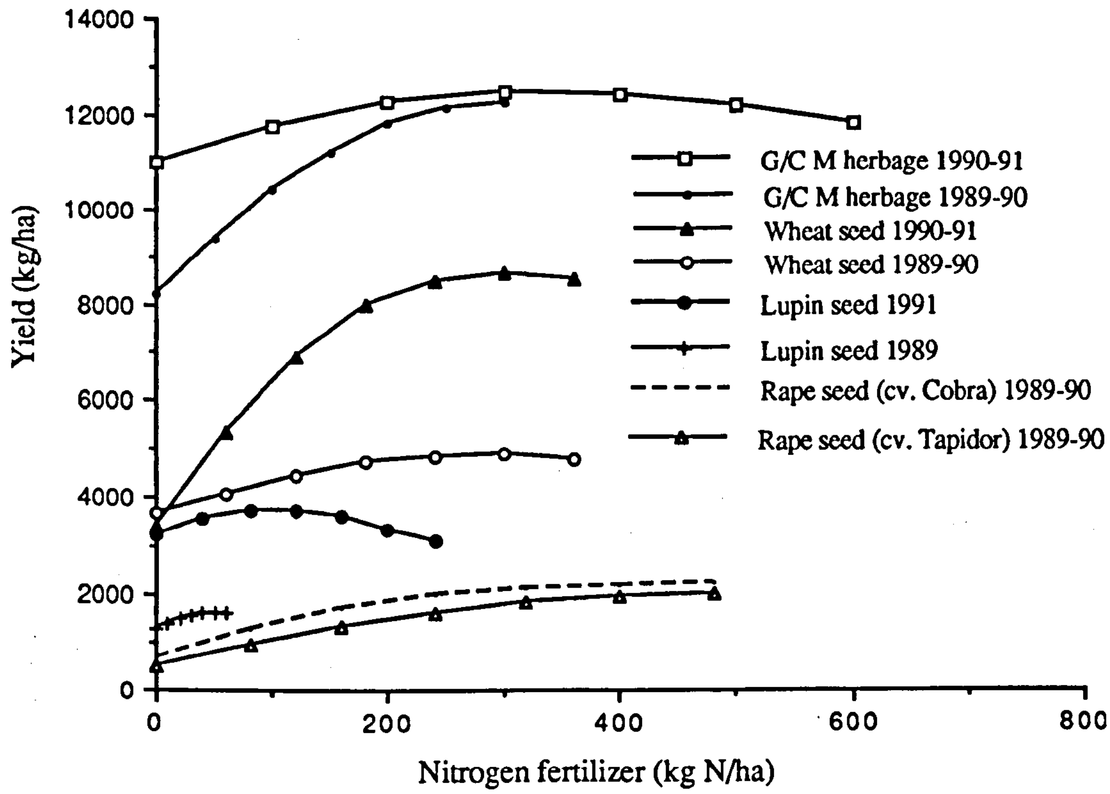

Fig 3.4-1. Comparison of crop yields in response to nitrogen fertilizer application, using the estimates from the response curves in the field experiments (F2EX90 and F2EX91). G/C M = ryegrass/clover mixture.

For wheat grain yield, the Y_m (4899 kg/ha) harvested in 1990 was only 56.6% that (8649 kg/ha) harvested in 1991 and Y_e showed a similar relationship. The N fertilizer requirement (for Y_m and Y_e) was estimated to be 280 kg N/ha (maximum) and 219 kg N/ha (economic) respectively in the first year, 300 kg N/ha (maximum) and 273 kg N/ha (economic) in the second year, which falls in the range (200 to 300 kg N/ha for maximum yield) from the two experiments described by Sylvester-bradley and George (1987). The N requirements of winter wheat highly exceeded the MAFF recommended level of 120 kg N/ha (MAFF 1983). The disagreement with the MAFF recommended level may reflect a peculiar price rate (FP/PP = 2.12, Chapter 1; Table 1.5-1) used in the calculation or suggest that the utilization of nitrogen by the crop was quite specific for this particular experimental site and/or years under study.

Despite the drought in 1989 - 90, there was evidence that wheat responded to increasing nitrogen although the magnitude of this response was clearly damped. Interestingly, however, both yield responses indicated that nitrogen applications may be excessive and that yield reductions could occur.

For total biomass yields of the ryegrass/clover mixture, the N fertilizer rates for economic responses were up to 280 kg N/ha in 1989 - 90 and 245 kg N/ha in 1990 - 91 respectively, being close to the literature reported range for nitrogen application to maintain an optimum production of ryegrass/clover mixture (300 to 360 kg N/ha) (Daly 1987). The model fit for the total biomass yield of the ryegrass/clover mixture to N fertilizer in 1989 - 90 may not be the best since it poorly estimated the observed yield (Fig 3.2.2-3) at 240 kg N/ha, but no better fit could be obtained with alternative models.

The responses of the ryegrass/clover mixture to fertilizer were quite different in the two cropping seasons. This may caused by a number of factors which contributed the yield in the low nitrogen plots. Firstly, the spring drought in 1990 may limit both the mineralization of soil organic nitrogen and the crop growth in the drought season and consequently reserved the soil source of nitrogen available for the following cropping season. Secondly, from the personal observation, the white clover in the mixture grew poorly in the drought spring 1990 in all plots, but more vigorously in the low fertilizer plots than in the high fertilizer plots in 1991, which may enhance the response of the mixture to nitrogen in 1990 and tend to diminish the differences in fertilizer application in 1991. The maximum yield in both cropping seasons was apparently limited by the factors other than fertilizer.

In 1989 - 90, optimum estimated rates of nitrogen fertilizer for rape were 310 kg N/ha for Cobra and 359 kg N/ha for Tapidor, which agrees with the literature conclusion of 300 kg N/ha for a maximum seed yield of 3.7 t/ha from long-term trials (Tribott-Blondel 1988). These levels of N application substantially exceeded the recommended level of 226 kg N/ha (MAFF 1983). This may be resulted in a specific price rate (FP/PP = 1.35, Chapter 1; Table 1.5-1) used in the calculation or reflected a variation on the site or years under the experiment. The noticeable difference between the two rape cultivars in biomass response to nitrogen (Fig 3.2.2-4) implies that cv. Cobra may be able to use available nitrogen more efficiently to build up total biomass yield and in turn to increase seed yield. Differential response to other factors such as water supply, incident radiation and temperature may also underlie these differences. To identify the relative contributions of such factors, further work is needed.

The data for lupins in 1991 suggested that an optimum application of 83 kg N/ha was needed for an economic response in terms of seed yield (3.77 t/ha) though it is widely accepted that nitrogen fertilizer is not needed for a legume crop (MAFF 1983). However the additional yield gained from 83 kg N/ha was relatively small (560 kg/ha).

In the absence of nitrogen for both crops, average seed yield of lupin was 3.21 $\pm$ 0.10 t/ha, being almost the same seed yield as for wheat (3.34 $\pm$ 0.41 t/ha). Wheat, however, showed a considerable yield increase in relation to available nitrogen. These results may suggests that lupin is able to utilize both soil mineral nitrogen and symbiotically fixed N in a complementary manner. The same conclusion was reached by Duthion and Amarger (1989) in a field experiment, which showed that maximum seed yield was produced at the nitrogen fertilizer application of 80 - 160 kg N/ha.

Amongst the four crops in experiments (F2EX90 and F2EX91), the highest optimum N level was demanded by rape which, however, produced the lowest crude protein per hectare. This may reflect the unique biological nature of rape having an excessive consumption of nitrogen and low rate of nitrogen translocation from its vegetative parts to the seed at later growth stage when high rates of nitrogen are applied (Tribott-Blondel 1988; Kullmann and Geisler 1988).

The ryegrass/clover mixture required almost the same amount of nitrogen as wheat but produced 3 to 4 times as much protein per hectare than wheat. Not only does this result suggest that the ryegrass/clover mixture utilized N more efficiently than wheat but it also emphasizes the role of clover in the nitrogen fixation. In this experiment, atmospheric N_2 fixation, however, was not measured. Rodriguez (1988) estimated that 50 to 160 kg N/ha may be fixed annually by clover (*T. repens*) according to the density of clover in a sward.

The optimum N fertilizer required by lupin characterized its flexibility in nitrogen utilization as a legume crop. At the level of 30% N fertilizer applied to wheat, lupin could produce 1.74 fold more crude protein/ha than wheat and in the absence of N fertilizer it could produce 1296 kg/ha crude protein. This was 3.4 fold higher than that of wheat with no nitrogen fertilizer supplied and 1.6 fold greater than that of wheat at a nitrogen fertilizer application of 273 kg N/ha. On the other hand, the cost of such nitrogen fixation was high since maximum dry matter/ha of lupin was only 43.7% of the maximum yield of the wheat. But in the absence of N fertilizer, lupin dry matter/ha was 96.1% of wheat, reflecting the poor yield performance of wheat at a low level of N supply.

Lupin, wheat and the ryegrass/clover mixture exhibited a reduction of yield at the high fertilizer levels in the experiments (Fig 3.4-1). This may be caused by a decrease in soil water content due to an increase in transpiration of increased biomass at the high fertilizer applications although other factors such as a root damage or effects on the assimilates allocation in lupin and wheat production were also possibly to reduce yield. To identify those factors, however, further work is needed.

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CHAPTER 4 THE COMPARISON OF DRY MATTER ACCUMULATION, GROWTH PATTERNS AND NITROGEN UTILIZATION

4.1 Introduction

An understanding of the basic growth patterns of crops is essential for profitable decision making, particularly in relation to the timing of nitrogen fertilizer application. Harvestable yield is ultimately the product of growth (cell division and expansion) which in turn is dependent on external environmental and internal physiological factors (Stoskopf 1981). Yield is also the product of yield components which are formed during different growth stages. Yield formation varies amongst wheat, rape, lupin and a ryegrass/clover mixture.

Wheat grows typically through 9 major growth stages, namely seedling growth, tillering, stem elongation, booting, ear emergence, flowering, milk stage, dough and ripening (Tottman and Makepeace 1979; Harper 1983). In the early stages, growth is associated with the production of leaves and tillers (seedling growth and tillering) and followed by a period of stem elongation with associated expansion of leaves (stem elongation and booting). Over the growth period of stem elongation and booting, daily uptake of nitrogen is the highest and in favorable conditions this rate could be as high as 4 - 5 kg N/ha/day (Kretschmer 1989). As the final leaf expands, the rate of stem elongation is reduced and the emergence of the previously formed inflorescence occurs. Up to flowering, wheat may accumulate 72 - 89% (Pandrangi and Wankhade 1989; Darroch and Fowler 1990) of the final aboveground nitrogen and 70% of final aboveground dry matter (Darroch and Fowler 1990) in tillers. The desired yield (seed) forms by the development of the zygote and morphologically is evident from the 'milk stage' and onwards. During seed formation, 26% to 52% (Pandrangi and Wankhade 1989; Darroch and Fowler 1990) of previously accumulated nitrogen may be translocated from tillers to seed. Using the published data of Darroch and Fowler (1990), it can be calculated that in contrast only 12% of photosynthetic assimilates may be translocated from tillers to seed after flowering and up to maturity (Harper 1983).

The growth of oilseed rape follows a course of seedling growth, leaf expansion, stem elongation, branching, flowering, pod development and seed ripening (Harper and Berkenkamp 1975). After germination, the seedling of oilseed rape develops a rosette of leaves which undergo expansion before the onset of stem elongation. The growth at these stages is more responsive to nitrogen fertilizer than at others (Allen and Ridgman 1971). Stem elongation involves the growth of a branched structure with the production of a large number of smaller leaves. Towards flowering, the proportion of leaf dry matter declines and the plant starts to produce a large number of flower buds which signify the end of the rapid vegetative growth and the onset of flowering. In Britain, flowering occurs over a period from late May to early July in autumn sown rape and early June to mid July in spring sown rape. Rape shows an indeterminate growth habit and flowering overlaps with pod development and seed growth. At these latter stages, the growth of stems and pods is more affected by soil water conditions than nitrogen fertilizer (Rood and Major 1984) and the decline in leaf weight continues until largely all leaves have senesced and been lost at harvest (Munir 1982). Seed is formed at the final growth stage and grows with associated translocation of accumulated nitrogen from old leaves and stems to the growing seed whilst the photosynthesis of the stems and pods are still active till maturity (Ogunlela, Kullmann and Geisler 1990; Spedding 1983). The subject of dry matter and nitrogen accumulation and distribution in rape has not attracted much research in recent years. A literature search on the Institute for Scientific Information Database yielded only two papers directly addressing this subject over the period 1984 - 1992.

From personal observation, the growth stages of a lupin crop may consist of seedling growth, stem elongation and leaf expansion, branching, flowering, pod development and seed ripening. After germination, the cotyledon of a lupin crop provides the only source of photosynthetic assimilates before the first true leaf unfolds which usually occurs one week or ten days after germination. Root growth is more active than the growth of above ground parts at this stage. It was observed that roots may grow to 30 cm in length before the first true leaf unfolded and may reach a depth of 1 metre by the time fourth true leaf has unfolded. At these respective stages stems are on average 5 cm and 20 cm in height and the root dry weight is about 30% to 50% of the total dry matter respectively. Leaf expansion is associated with stem elongation. An early supply of a small amount of nitrogen fertilizer at these stages may result in a high dry matter accumulation early in the season (Duthion and Amarger 1989). The plant develops a branched structure after four node expansion with associated leaf area development and flower initiation. In the U.K., flowering occurs over a period from early June to late July in spring sown lupin, and shows an indeterminate growth habit. As the pod develops the rate of stem elongation is reduced which indicates the onset of seed development. Leaf area per plant does not decline until shortly before seed maturity. At the stage of seed filling, both the leaves, stems and pods of lupin are equally important in providing photosynthetic assimilates for seed yield and translocation of previously accumulated nitrogen from leaves, stems and pods to seed takes place. This amount of nitrogen may be as high as 53% of the total seed nitrogen at harvest. The growth habit of lupin results in a dry matter harvest index of about 40% of the total above ground biomass and nitrogen harvest index of 80% of total above ground nitrogen (Duthion and Amarger 1987). As with rape, the subject of dry matter and nitrogen accumulation and distribution in lupins has not received much attention.

A ryegrass/clover mixture mixes biennial (*Lolium multiflorum L.*) and perennial (*Lolium perenne L.*) ryegrass and white clover (*Trifolium repens L.*) together. The advantage of the mixture is that it can give a high yield for the first year after sowing and sustain high yields in the following years (Williams 1980). Although the individual component species of the mixture have their own characteristics of growth and development, the growth of the mixture as a whole is simplified by regular cuttings since stems and inflorescence are removed regularly and further development of the life cycle is prohibited. The continual removal of herbage biomass by cutting results in a reduction of leaf area index and loss of interception of radiation thus causing the rate of photosynthesis to decline. The re-growth of the mixture therefore involves a vertical expansion of remaining leaves, development of new tillers and new leaf expansion until the next cut. The yearly production of the ryegrass/clover mixture is merely the cumulative yield of all cuts which is often influenced by seasonal variance in incident radiation, temperature, water and nutrient supply.

Because of the different growth forms of wheat, rape, lupin and the ryegrass/clover mixture, the nitrogen fertilizer practice is often adjusted both in frequency and quantity of application to ensure maximization of the desired yield of the crops.

In wheat, most of nitrogen fertilizer is usually applied before the onset of the main natural flush of tillering (Harper 1983) and at the time of the first detectable node since this will increase the numbers of fertile tillers and hence seed yield (Pandrangi and Wankhade 1989).

In oilseed rape, an adequate supply of nitrogen after seed germination and before the onset of stem elongation is important for the development of leaves, and hence maximization of seed yield. At a high rate of nitrogen supply, oilseed rape, however, takes up nitrogen into leaves, stem and seed throughout the growing season till shortly before seed filling is complete, whereas at a low rate of nitrogen supply a large part of the N accumulated in its vegetative parts and pod may be translocated into seed (Kullmann and Geisler 1988).

A split nitrogen application is usually practiced on ryegrass/clover mixtures after each cut period to stimulate vegetative growth (Ledgard and Steele 1988). A ryegrass/clover mixture needs to be adequately and continuously supplied with nitrogen fertilizer up to 300 to 360 kg N/ha annually and a 4 or 5 split application is usually practiced (Daly 1987).

A split application of nitrogen fertilizer is unnecessary for lupin (Duthion and Amarger 1989), but the supply of nitrogen fertilizer immediately after germination may stimulate growth since lupin does not fix atmospheric N_2 until 20 or 30 days after seed germination (Duthion and Amarger 1987).

This chapter describes two experiments designed to examine the growth of the four crops in detail. In the first (experiment PE190), the pattern of growth of the four crops is examined under different nitrogen regimes; in the second (experiment PE290) the response of lupin and rape are considered in relation to nitrogen regimes and planting density. Since dry matter accumulation, growth patterns and nitrogen utilization of a crop will be affected by planting density (Langer and Liew 1973; Singh and Singh 1984; Duthion and Amarger 1989), the same planting density as used in previous field experiment was used in experiment (PE190).

4.2 Comparison of growth patterns in wheat, rape, lupin and a ryegrass/clover mixture (experiment PE190)

4.2.1 Materials and Methods

Experiment procedures

An experiment, coded as PE190, was set up to examine the growth patterns and nitrogen utilization of wheat, rape, lupin and a ryegrass/clover mixture. Plants were raised in a 3.5-metre wide and 35-metre length polythene tunnel to maximize the time available for growth, to provide a fully controlled water supply and freedom from attack by insects and birds. The experiment was conducted from February to October in 1990.

The experimental design was a randomized complete block (3 blocks). A partial factorial arrangement of treatments was employed involving two overall total nitrogen applications, each split in time of application, four crops and up to seven destructive harvests throughout the growing season. Nitrogen was applied at two growth stages for wheat, rape and lupin, namely in the seed bed and when plants had germinated and been thinned to standard densities as in the field experiments described in Chapters 2 and 3. For the ryegrass/clover mixture, nitrogen was applied after each cutting. Two levels, below and above the maximum response, of nitrogen fertilizer application were chosen based on the observations of the individual response curves of the crops in the field experiment. These treatments gave 38 combinations, each replicated three times (Table 4.2.1-1).

Seeds were sown at 1 cm depth into soil in 26.7 cm diameter pots (surface area 0.056 m^2), soil depth being 28 cm. A commercial soil compost (John Innes seed compost) was used since it contained a very low baseline of nitrogen fertilizer. A manned irrigation system was established to supply water.

Harvest

At harvests, the plants were cut at ground level and half of the harvested material of each pot was dried at 100^{0}C (18 hours) for dry matter measurement and half dried at 65^{0}C (two days) for subsequent nitrogen assessment. Pots were then emptied and soil and root material air-dried for two days after which root material was separated from the soil manually. At the final harvest, the harvesting procedures were as above except for the seed of wheat, rape and lupin being separated and measured.

Dry matter referred to below is defined as the biomass of whole plant including seed, stem and root, dried at 100^0 C for 18 hours. In other instances it is prefixed as above ground or root as appropriate.

Table 4.2.1-1. Experimental details of experiment PE190. G/C M = ryegrass/clover mixture, GH = Grasslands Huia.

	Wheat	Lupin	Rape	G/C M		
Variety	AVALON	PRIMORSK	COBRA	ANTRIM	RVP	GH
Seeds/pot	25	12	12	65	65	160
Plants/pot	14	4	4			
Sowing date	17/2/90	17/2/90	17/2/90	17/2/90		
1st harvest	3/3/90	9/3/90	7/3/90	9/3/90		
2nd harvest	3/4/90	3/4/90	3/4/90	3/4/90		
3rd harvest	31/5/90	31/5/90	31/5/90	31/5/90		
4th harvest	29/7/90	13/7/90	13/7/90	13/7/90		
5th harvest				1/8/90		
6th harvest				24/8/90		
7th harvest				22/10/90		
Growing period	149	127	129	222		

The N fertilizer used in the experiment was 'NITRAM' (NH_4NO_3, 34.5% N) and Tables 4.2.1-2 and 4.2.1-3 give the N application rates, which were specific for the individual crops.

Table 4.2.1-2. Experimental details: fertilizer application (nitram g/pot) for wheat, lupin and rape (experiment PE190).

	Low level nitrogen			High level nitrogen		
Crop	Seedbed	Established	Total	Seedbed	Established	Total
Wheat	0.45	2.55	3	0.9	5.1	6
Lupin	0	0	0	0.15	0.46	0.61
Rape	0.6	3.4	4	1.2	6.8	8
Check	--	--	0	5.8	--	5.8

Table 4.2.1-3. Experimental details: fertilizer application (nitram g/pot) for the ryegrass/clover mixture (experiment PE190).

	Timing of N dressing (date/month in 1990)							
	Seedbed	21/3	3/4	4/6	18/7	2/8	24/8	Total
Low level	0.52	.0.2	0.2	0.8	0.8	0.8	0.8	4.12
High level	1.04	0.4	0.2	1.6	1.6	1.6	1.6	8.24

Nitrogen assessment

An additional 12 plots were incorporated as a check (6 pots with neither plants nor nitrogen application and 6 pots without plants but receiving N at an application rate of 360 kg N/ha).

Extractable nitrogen content of the soil was determined before the vigorous vegetative growth (28 days after germination) and after seed maturity for wheat, lupin and rape or at the end of the experiment for the ryegrass/clover mixture. The analytical methods are given in Chapter 2.

To ensure sufficient supply of phosphate and potassium, 3.7 grammes of ICI No 12 fertilizer (N, P, K, = 0, 8.73%, 26.56%) were applied to each pot before the start of the experiment. This application equates to 690 Kg/ha.

Since a ryegrass/clover mixture was included in the experiment it is impossible to represent the results in terms of an individual plant for this crop. The data on dry matter and nitrogen accumulation therefore is reported here on a unit of area basis (per pot). Where analysis of variance is employed to examine interactions amongst factors it should be noted that absolute nitrogen levels are not comparable (Tables 4.2.1-2 and 4.2.1-3) and that terms examine changes in arbitrary level only.

4.2.2 Results

(1) Dry matter accumulation per unit area

At the final harvest, the total above ground biomass, seed/herbage yield and root biomass of all crops were significantly different ($p < 0.01$) from one another (Tables 4.2.2-1 to 3). Nitrogen fertilizer level on average significantly affected ($p < 0.01$) both the above ground biomass and economic yield, but not root biomass ($p > 0.05$) of the crops. For above ground and root biomass, there were differences ($0.01 < p < 0.05$) among blocks, whilst no differences ($p > 0.05$) among blocks were apparent for economic yield. There was also a significant ($p < 0.01$) crop * fertilizer interaction term for above ground biomass and economic yield. This interaction term was not significant ($p > 0.05$) for root biomass.

Table 4.2.2-1. Analysis of variance of above ground biomass of wheat, ryegrass/clover mixture, lupin and rape at the final harvest (experiment PE190).

Source	DF	Sum of squares	F	P_{HO}
Crop	3	12360.57	48.9	0.0001
Fertilizer	1	5266.23	62.5	0.0001
Block	2	804.15	4.8	0.0263
Crop*fertilizer	3	3400.6	13.5	0.0002
Error	14	1179.69		
Total	23	23011.24		

Table 4.2.2-2. Analysis of variance of economic yield of wheat, ryegrass/clover mixture, lupin and rape at the final harvest (experiment PE190).

Source	DF	Sum of squares	F	P_{HO}
Crop	3	76837.59	685.1	0.0001
Fertilizer	1	783.95	21.0	0.0004
Block	2	164.91	2.2	0.1470
Crop*fertilizer	3	680.81	6.1	0.0072
Error	14	523.41		
Total	23	78990.67		

Table 4.2.2-3. Analysis of variance of root biomass of wheat, ryegrass/clover mixture, lupin and rape at the final harvest (experiment PE190).

Source	DF	Sum of squares	F	P_{HO}
Crop	3	37559.1	65.97	0.0001
Fertilizer	1	32.7	0.17	0.6844
Block	2	1483.7	3.91	0.0448
Crop*fertilizer	3	307.7	0.54	0.6624
Error	14	2656.8		
Total	23	42039.9		

The pattern of dry matter accumulation per unit area of each crop in relation to nitrogen fertilizer levels is illustrated in Fig 4.2.2-1. Fig 4.2.2-1 shows that the basic pattern of dry matter accumulation in wheat and rape was different from that of lupin and the ryegrass/clover mixture, over the growing season.

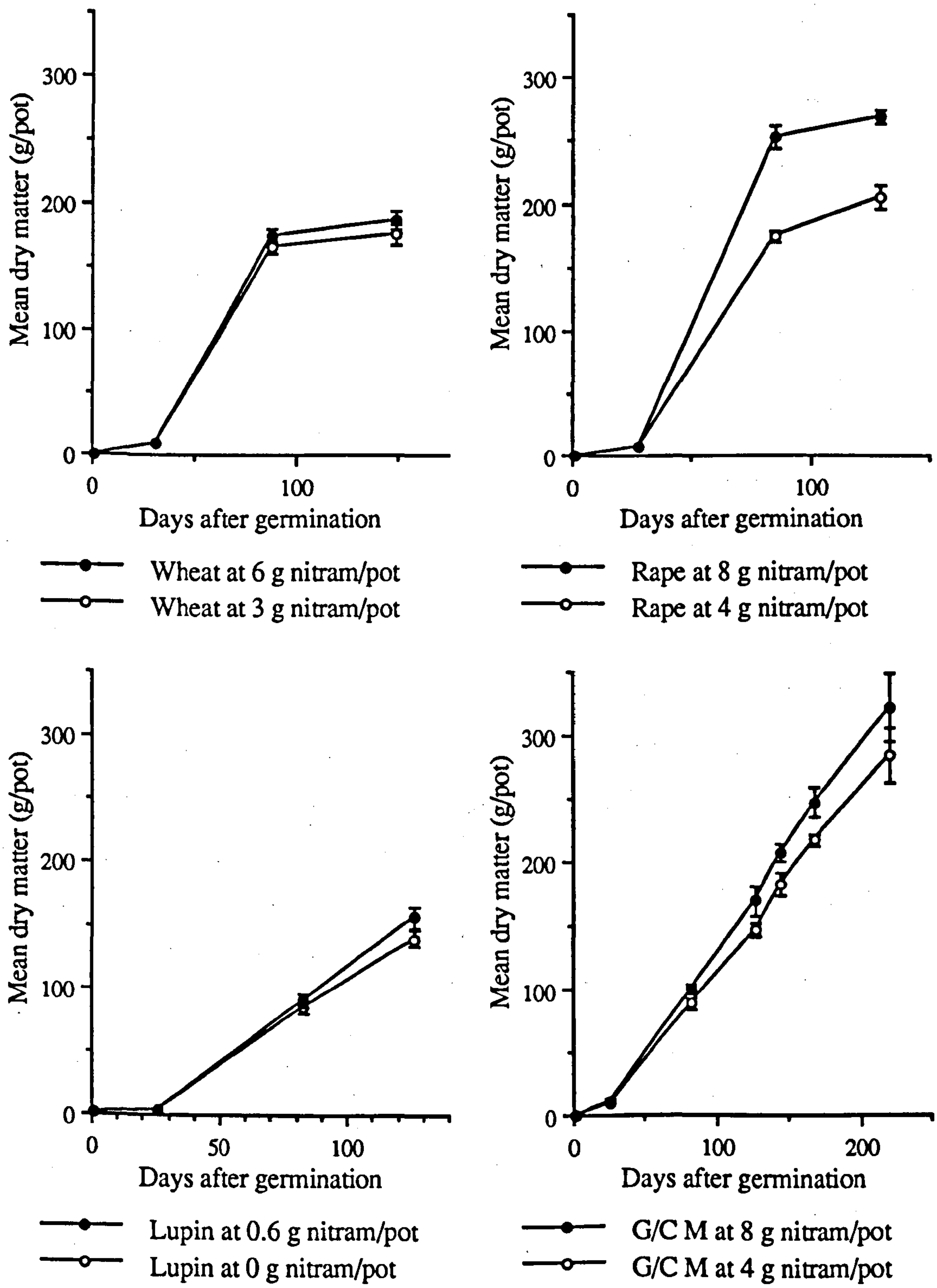


Fig 4.2.2-1. Comparison of total dry matter (root and shoot) accumulation per unit area of the crops at different levels of nitrogen application (experiment PE190). Confidence limits are standard errors of the mean. Note scale on the abscissa differ since crops matured at different times.

Although all crops displayed a small dry matter increment at the second harvest and a considerably larger one by the third, the pattern of dry accumulation in wheat and rape differed conspicuously from that in lupin and the ryegrass/clover mixture. In the former seed crops accumulation was phasic with most biomass accrued after 103 days (3rd harvest) and little added subsequently. In lupin and the ryegrass/clover mixture biomass accumulation occurred at approximately a constant rate after the first harvest. Nitrogen fertilizer applications did not significantly effect ($p > 0.05$) dry matter present at the first harvest, but did so at the second harvest ($p < 0.013$) and conspicuously so ($p < 0.01$) at the 3rd and 4th harvests (Appendix C, Tables C-1 and C-2 for analysis of variance). Crops, however, responded differently ($p < 0.01$) to nitrogen fertilizer addition at the 3rd and 4th harvests. In wheat and lupin, dry matter was statistically similar (LSD = 1.14, 12.88 and 18.85 g/pot for the 2nd, 3rd and 4th harvest respectively) between nitrogen fertilizer treatments at all harvests. In contrast, rape responded noticeably to nitrogen fertilizer, a difference of 77.6 g being apparent at the 3rd harvest. In the ryegrass/clover mixture, a doubling of nitrogen application increased the rate of biomass accumulation.

The partitioning of dry matter accumulation (per unit area) between root and shoot changed over time amongst the crops (Figs 4.2.2-2, 3, 4).

After 14 days growth, the above ground dry matter of lupin was 7.3 fold greater than that of wheat, 9.2 fold greater than that of the ryegrass/clover mixture and 29.8 fold higher than that of rape. In contrast lupin root dry matter was only about one-third that of wheat, equal to that of the ryegrass/clover mixture and 11.6 times greater than that of rape (Fig4.2.2-2, calculation of LSD is given in Appendix B).

By the second harvest (45 days) from sowing, wheat, the ryegrass/clover mixture and rape had grown faster than lupin, as reflected in the higher dry matter at the second harvest (Fig4.2.2-3).

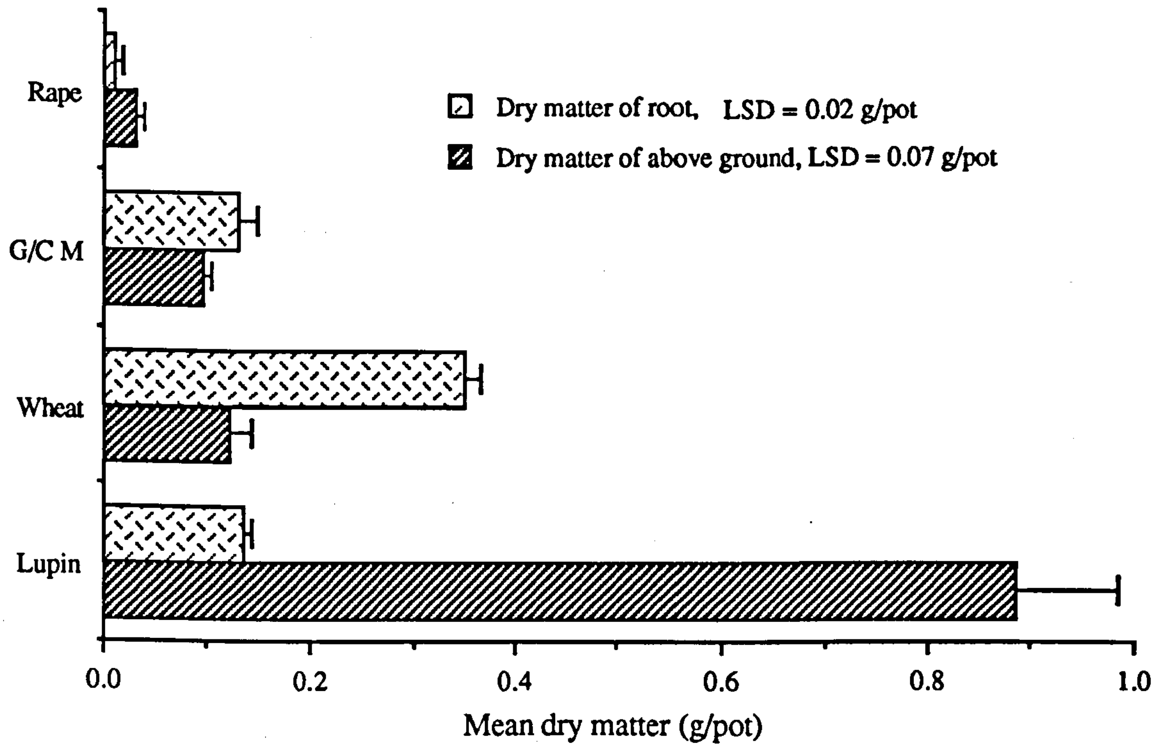


Fig 4.2.2-2. Dry matter per unit area 11 days after sowing. Data are meaned over fertilizer application (experiment PE190). Confidence limits are standard errors of the mean. G/C M = ryegrass/clover mixture. Not differing abscissa from Fig 4.2.2-3.

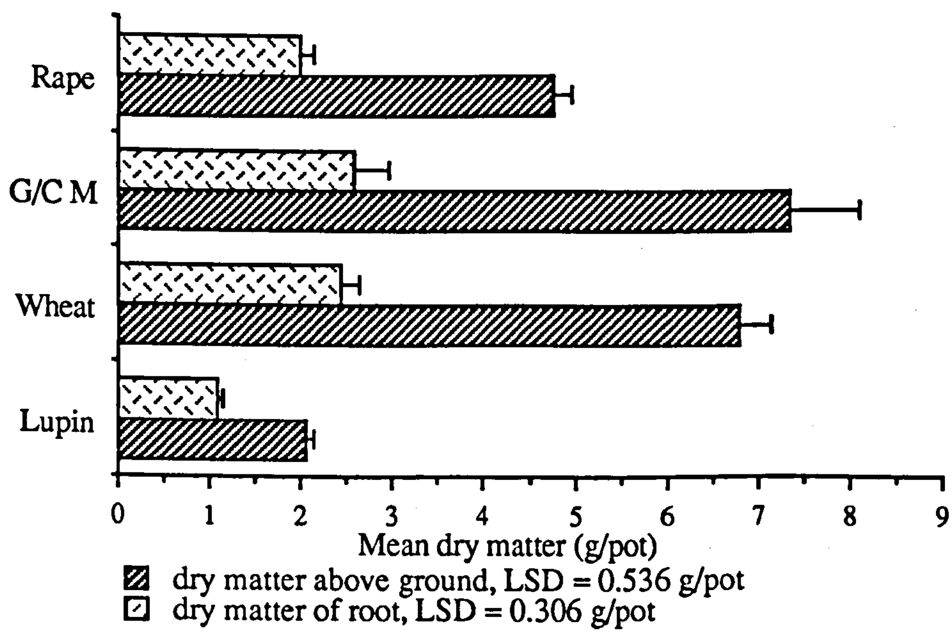


Fig 4.2.2-3. Comparison of dry matter of the crops at the second harvest (45 days after sowing). Data are meaned over fertilizer application (experiment PE190). Confidence limits are standard errors of the mean. G/C M = ryegrass/clover mixture. Not differing abscissa from Fig 4.2.2-2.

Comparison of Figs 4.2.2-2 and 3 indicates that the partition of photosynthetic assimilates into above and below ground plant biomass was different amongst the crops in early growth. Rape showed an equal partitioning of above and below ground biomass at the first and second harvests (34%). In wheat and the ryegrass/clover mixture, however, root biomass exceeded above ground biomass at the first harvest, but this had reversed after 45 days of growth. Contrastingly lupin root biomass being 15% of the above ground biomass at the first harvest increased to 55% of the above ground at the second harvest.

These patterns of dry matter accumulation and the development of yield resulted in significant differences amongst the crops (Fig 4.2.2-4) and caused significant differential responses of the crops to nitrogen in terms of above ground biomass and economic yield (Tables 4.2.2-1 and 4.2.2-2), but not root biomass (Tables 4.2.2-3).

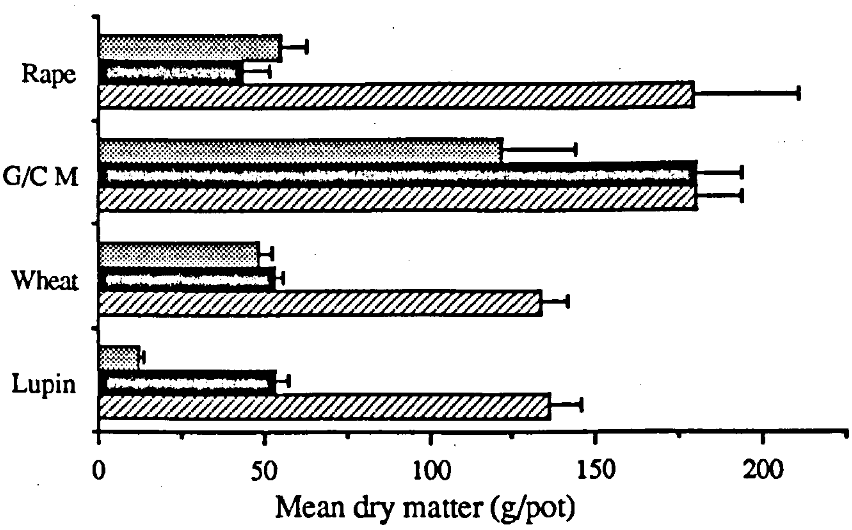


Fig 4.2.2-4. Comparison of yield of crops at the final harvest, using pooled data over fertilizer application (experiment PE190). Confidence limits are standard errors of the mean.

- Above ground biomass, LSD = 11.37 g/pot
- Economic yield, LSD = 7.57 g/pot
- Root biomass, LSD = 17.06 g/pot

The ryegrass/clover mixture (180.5 g/pot) gave the highest economic yield of all the crops, root biomass being 67% of above ground biomass. Although the above ground biomass of wheat and lupin were statistically similar and less than that of rape ($p < 0.01$), the economic yields were greater ($p < 0.01$) than that of rape.

At the final harvest, root biomass per pot of wheat and rape were similar but root material contributed a greater proportion to total biomass in wheat as compared with rape. Interestingly lupin root biomass constituted the smallest fraction of total biomass of all four crops at the final harvest.

(2) Relative growth rates of crops

The differences in the growth patterns of the four crops were examined through the analysis of relative growth rate (Fig 4.2.2-5).

Relative growth rate, RGR (Harper 1983; Austin 1964), is defined as

$$RGR = \frac{Log_e W_2 - Log_e W_1}{T_2 - T_1}$$

where RGR is the relative growth rate (g/g/day), W_2 and W_1 are total dry matter (g, above and below ground dry matter) per pot harvested on days of T_2 and T_1 after germination respectively.

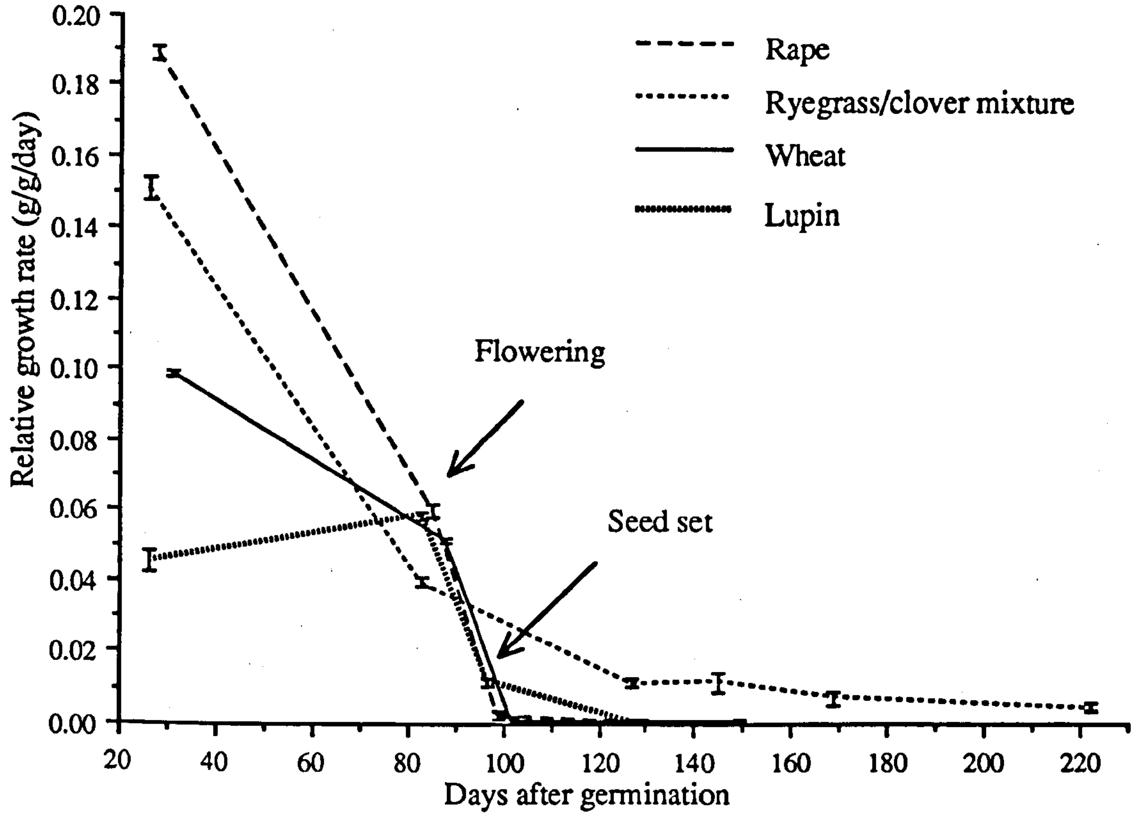


Fig 4.2.2-5. Comparison of relative growth rate of the crops, using pooled data over fertilizer application (experiment PE190). Confidence limits are the standard errors of the mean.

In the seed crops, the relative growth rate of wheat and rape was higher than that of lupin as measured over the first 28 days of growth, after which it declined rapidly to fall below that of lupin after 100 days, at crop maturity. In the ryegrass/clover mixture, mean relative growth rate was 0.15 g/g/day during initial leaf expansion and tillering (28 days after germination), and exhibited a continual decline throughout the experiment period. In contrast, lupin exhibited an initial low relative growth rate which increased during vegetative growth (28 - 80 days). It subsequently declined at a lower rate than wheat and rape, reflecting a continuous dry matter accumulation associated with flowering till seed maturity.

The effects of nitrogen fertilizer application were only detected in the early stages of growth of the crops with the exception of wheat (Fig 4.2.2-6).

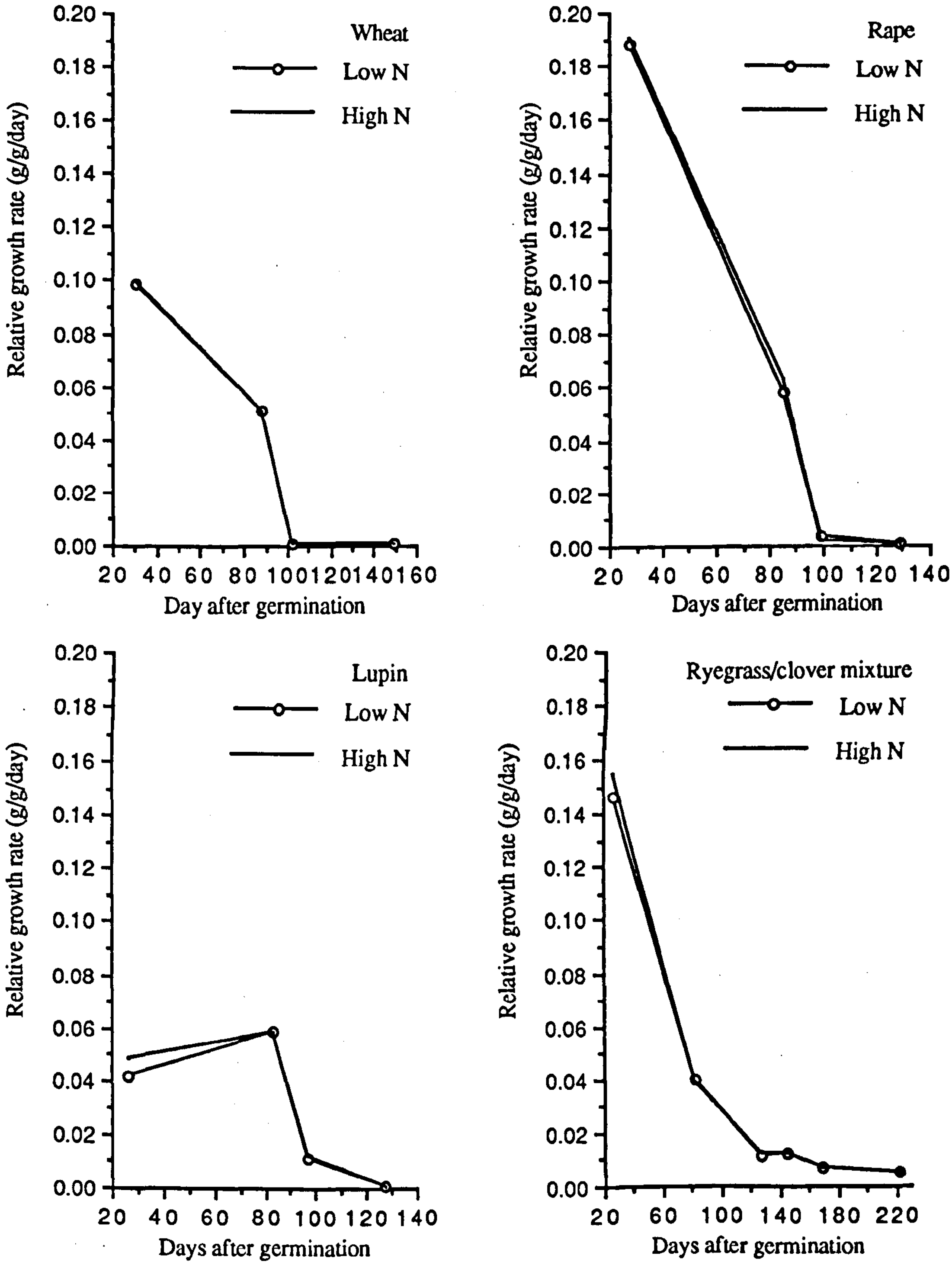


Fig 4.2.2-6. Effects of nitrogen application on the relative growth rate of the crops (experiment PE190).

(3) Fate of nitrogen

Nitrogen accumulation in biomass per unit area

Nitrogen accumulation in total plant dry matter (root, shoot and seed) per pot followed two basic patterns. Wheat and rape exhibited maximum nitrogen accumulation per unit area after 80 days at flowering and then declined from this peak, the loss being most marked in rape. In contrast, lupin and ryegrass/clover mixture showed a steady uptake of nitrogen until seed maturity in lupin and the final harvest in the ryegrass/clover mixture (Fig 4.2.2-7).

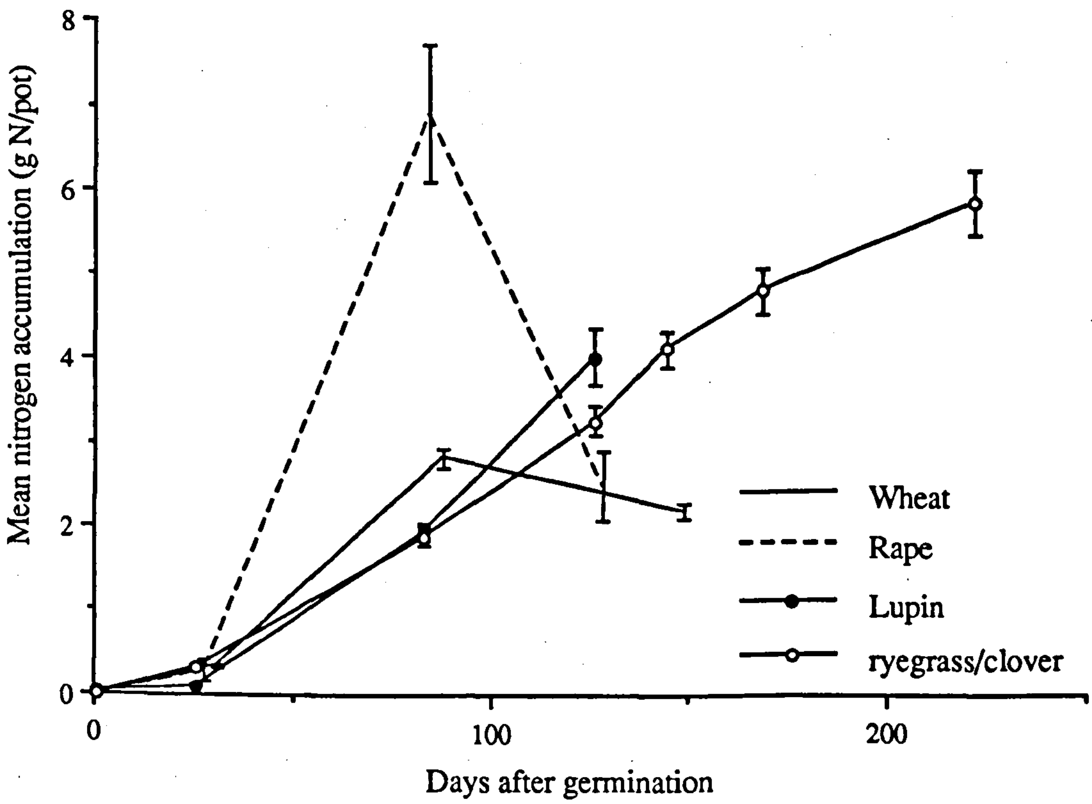


Fig 4.2.2-7. Comparison of nitrogen accumulation in the total dry matter per unit area of the crops, using pooled data over fertilizer application (experiment PE190). Confidence limits are standard errors of the mean.

The total amount of nitrogen held in dry matter per unit area at the final harvest is shown in Fig 4.2.2-8. Wheat contrasted with the other crops in that nitrogen yields were unaffected by nitrogen application treatment, whereas in all others the high N treatment elevated N yield. This was most conspicuous in rape, and with a small but significant increase in lupin.

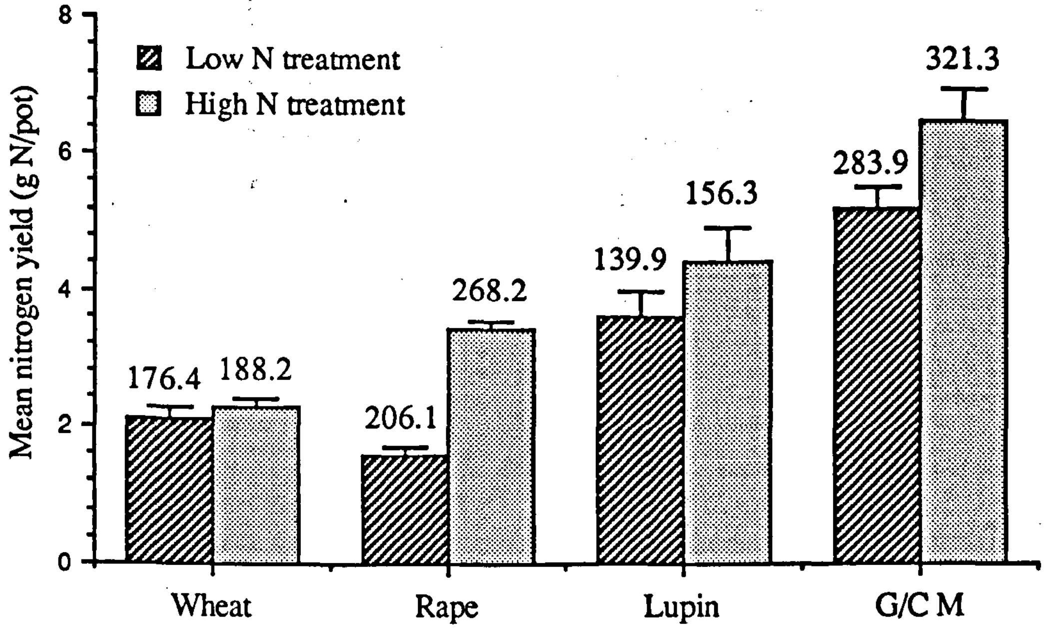


Fig 4.2.2-8. The effect of nitrogen fertilizer treatment on the total nitrogen yield in dry matter (per unit area) at the final harvest (experiment PE190). Confidence limits are the standard errors of the mean. The numbers at the top of each bar are the total dry matter yield (g/pot) at the final harvest. G/C M = ryegrass/clover mixture. Nitrogen fertilizer treatments are given in Tables 4.2.2-2 and 3. LSD = 0.85 g N/pot.

Extractable nitrogen in the soil

Soil extractable nitrogen assessments were analysed by a repeated measures analysis of variance (Table 4.2.2-4). All terms in the analysis of variance were significant and Fig 4.2.2-9 illustrates mean extractable N levels in the soil at the two observation dates. Extractable N in the soil 28 days after germination and at the final harvest varied in relation to crop and nitrogen application level. For the seed crop, higher extractable N was present in soil from pots receiving the high N level in comparison to the ryegrass/clover mixture. In all cases, however, lower amounts of N were extracted from soils containing crops under high N treatment in comparison to the check.

Table 4.2.2-4. Analysis of variance of soil extractable nitrogen (NO_3-N and NH_4-N) before vigorous vegetative growth (28 days after germination) and at the final harvest (experiment PE190). Fert = N fertilizer level, Harvest = 28.

Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	4	186.68	5.88	0.0027
Fert	1	169.01	21.30	0.0002
Crop*Fert	4	120.46	3.79	0.0188
Error	20	158.73		

Within harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	1	1254.37	154.66	0.0001
Harvest*Crop	4	175.14	5.40	0.0041
Harvest*Fert	1	149.03	18.37	0.0004
Harvest*Crop*Fert	4	123.51	3.81	0.0185
Error	20	162.21		

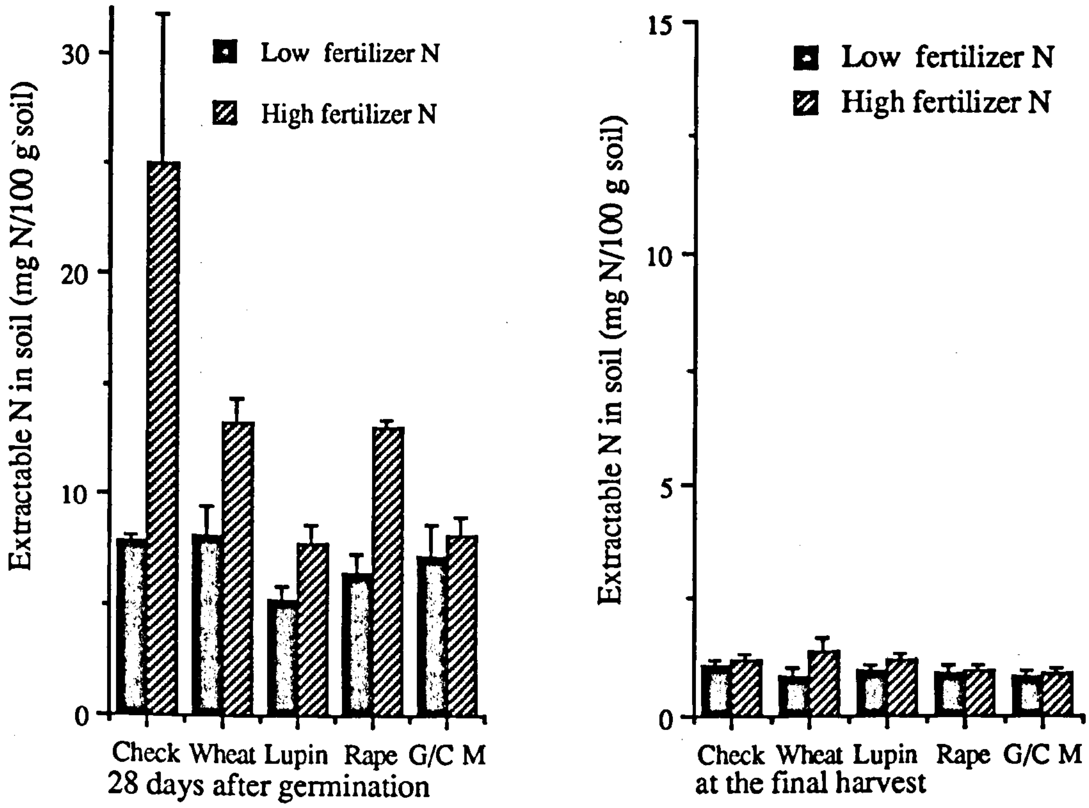


Fig 4.2.2-9. Comparison soil extractable nitrogen before vigorous vegetative growth (28 days after germination) and at the final harvest at two levels of nitrogen fertilizer application (experiment PE190). Confidence limits are standard errors of the mean. (G/C M = ryegrass/clover mixture, Check = without plants. Nitrogen levels are given in Tables 4.2.1-2 and 4.2.2-3).

Although analysis of variance indicated the soil extractable nitrogen content was significantly different between crops and between nitrogen fertilizer application, Fig 4.2.2-9 suggested that the scale of influence from these two sources was not great as the effect of time, which could be noticed as the changes within check (without plant and N fertilizer, without plant with N fertilizer).

4.3 Comparison of growth pattern and nitrogen utilization of rape and lupin (experiment PE290)

The previous experiment (PE190) indicated that responsiveness to nitrogen was most noticeable in rape and relatively small in lupin. The field experiments reported in Chapters 2 and 3 indicated that lupin required the least amount of nitrogen and maintained crude protein yield even in the absence of nitrogen fertilizer. In contrast rape required an excess, or approximately the same amount of N fertilizer as did the ryegrass/clover mixture but returned comparatively less crude protein yield. Characteristically plants of both lupin and rape are large and may show differing responses to resource limitations.

An experiment was conducted to investigate the influence of planting density on nitrogen uptake and pattern of growth in lupin and rape.

4.3.1 Materials and Methods

The experiment, coded PE290, was conducted in a 3.5-metre wide, 35-metre long polythene tunnel from 23rd May 1990 to 8th October 1990.

The experimental design was a randomized complete block design with three replicates. The two crops were sown individually in pots at crop specific planting densities and nitrogen application levels with 3 replicates sowing being made for 7 destructive harvests. This gave a total of 126 treatments (Table 4.3.1-1).

Pots were 26.7 cm in diameter (surface area of 0.056 m^2), soil (John Innes seed compost) depth being 28 cm. A manual irrigation system was established to supply water.

To ensure sufficient supply of phosphate and potassium, 3.7 grammes of ICI fertilizer No 12 (N, P, K, = 0, 8.73%, 26.56%) were uniformly distributed in each pot before sowing. The fertilizer application was equivalent to 690 Kg/ha. The N fertilizer used in the experiment was 'NITRAM' (NH_4NO_3, 34.5% N).

Harvesting took place at approximately 15-day intervals with the first harvest occurring on 1st June 1990 and the final harvest being made on 8th October 1990. After harvest of above ground biomass, plants being cut at ground level, root material was manually separated from soil, after each pot had been left to air-dry for about two days. Dry matter yield per pot was then estimated by combining root and above ground biomass estimates. Specific experimental details for each crop are summarized in the following table.

Table 4.3.1-1. Experimental details: planting density and nitrogen fertilizer application for lupin and rape (experiment PE290). FTL = First true leaf unfolded.

	Lupin (cv. PRIMORSK)			Rape (cv. COBRA)		
Treatment	Low	Mid	High	Low	Mid	High
Density (plants/pot)	1	3	5	4	8	16
Fertilizer:						
Seedbed, nitram g/pot	0	0.15	0.3	0.3	0.6	0.9
FTL, nitram g/pot	0	0.10	0.2	1.7	3.4	5.1
Total, nitram g/pot	0	0.25	0.5	2	4	6

Nitrogen assessment

Before and after the experiment, soil of each pot was sampled for total nitrogen assessment. Extractable nitrogen content of the soil in each pot was determined at each harvest. The analytical methods are given in Chapter 2.

4.3.2 Results of experiment (PE290)

For convenience, to compare the results amongst experiments across this thesis, the data in this experiment are mainly reported on a unit of area basis (per pot).

(1) Dry matter accumulation per unit area

The patterns of dry matter accumulation, effects of planting density on dry matter accumulation at harvests, and the differences in crop response to planting density (crop and planting density interactions) are illustrated in Fig 4.3.2-1.

Effects of N fertilizer application on dry matter accumulation at harvest, and the differences in crop response to nitrogen fertilizer application (crop and N fertilizer interactions) are represented in Fig 4.3.2-2.

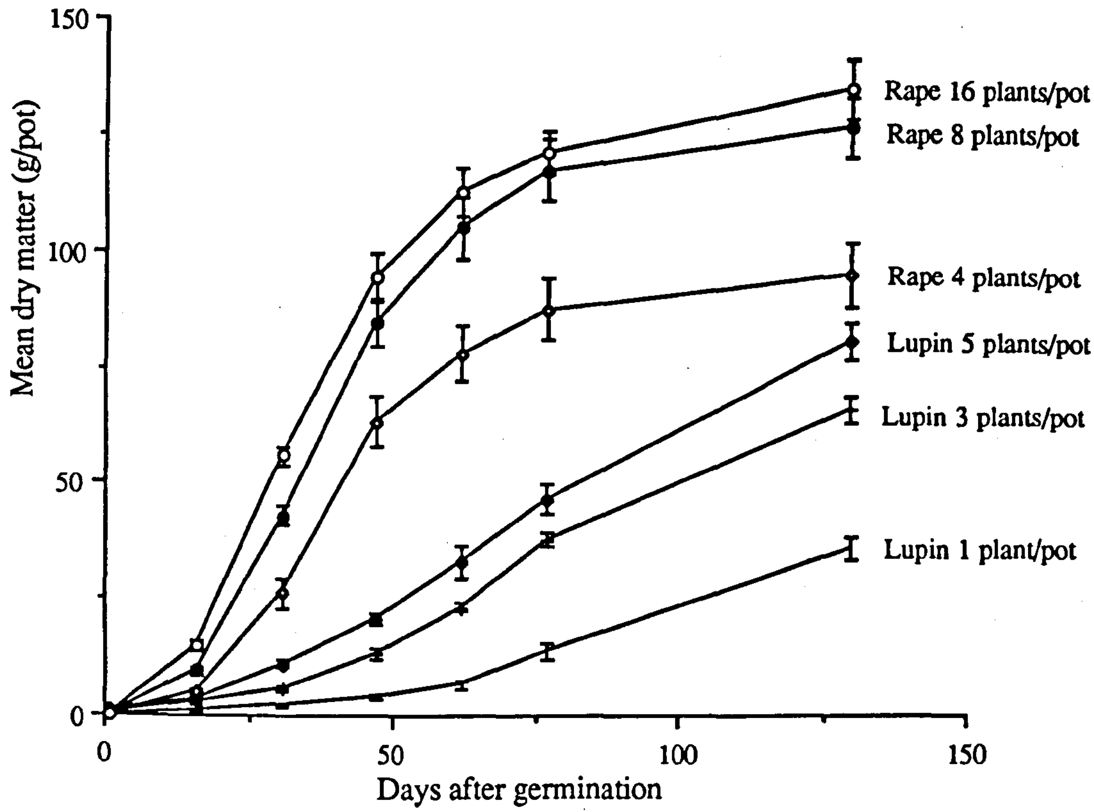


Fig 4.3.2-1. Comparison of the dry matter (above + below ground plant material) accumulation per unit area of lupin and rape at different planting densities, using pooled data over N fertilizer application (experiment PE290). Confidence limits are standard errors of the mean.

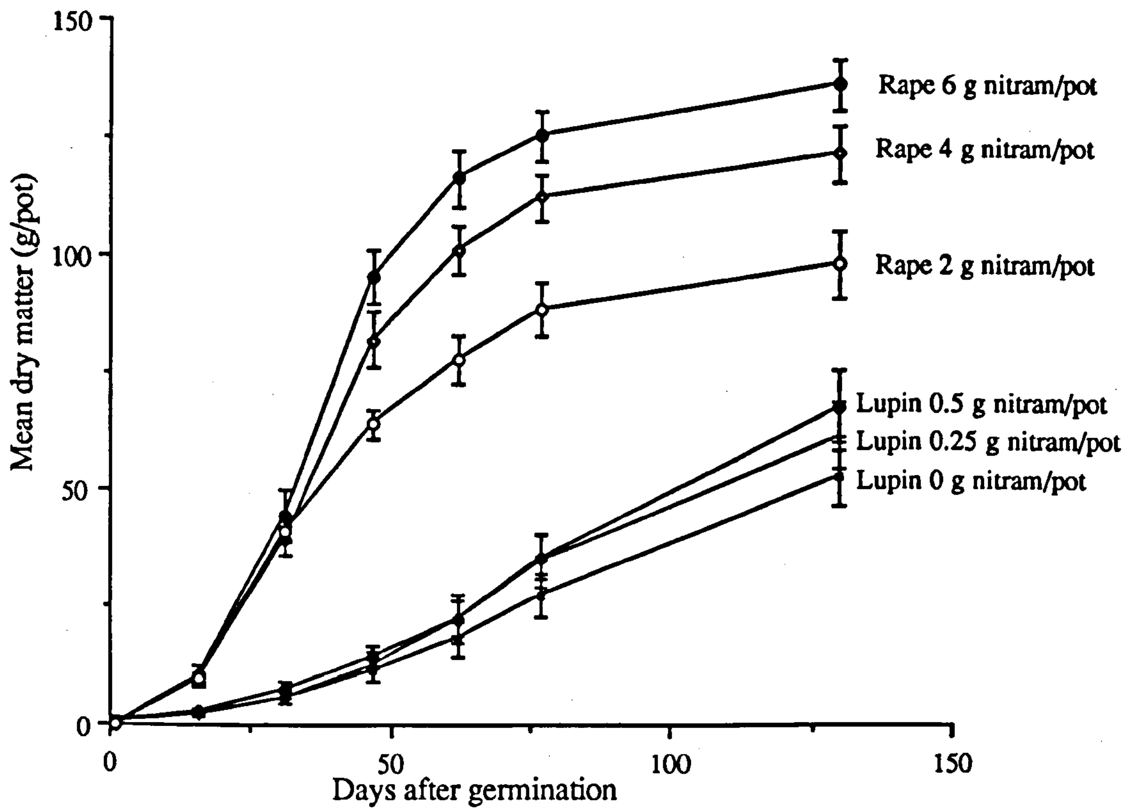


Fig 4.3.2-2. Comparison of the dry matter (above + below ground plant material) accumulation per unit area of lupin and rape at different N fertilizer application, using pooled data over planting densities (experiment PE290). Confidence limits are standard errors of the mean.

Analyses of variance, Table 4.3.2-1, were conducted separately on data from individual harvests to ensure homogeneity of error variance and indicated that the overall effects of density and crop were evident at all harvests ($p < 0.01$). The main effect of nitrogen fertilizer level was apparent ($p < 0.05$) at 38 days (3rd harvest) from sowing and remained significant ($p < 0.01$) from the 4th harvest until seed maturity (Table 4.3.2-1 and Fig 4.3.2-2).

First order interactions between crop * density and crop * fertilizer were significant at the first, fourth and fifth harvests. The changes in the levels of significance, as detected by analysis of variance signify that crops responded differently to levels of fertilizer and planting density at individual stages in their growth.

Table 4.3.2-1. Analysis of variance of dry matter yield of lupin and rape at each harvest (experiment PE290). Fert = N fertilizer, Den = planting density, C = crop.

Harvest	Source	DF	Sum of squares	F	P_{HO}
1st	Crop	1	6.5793	1194.8	0.0001
	Fert	2	0.0344	3.1	0.0568
	Den	2	3.2664	296.6	0.0001
	Block	2	0.0270	2.5	0.1014
	Crop*Fert	2	0.0344	3.1	0.0566
	Crop*Den	2	2.0146	182.9	0.0001
	Fert*Den	4	0.0273	1.2	0.3135
	C*Fert*Den	4	0.0260	1.2	0.3370
	Error	34	0.1872		
2nd	Crop	1	736.01	202.65	0.0001
	Fert	2	4.81	0.66	0.5222
	Den	2	363.86	50.09	0.0001
	Block	2	23.10	3.18	0.0542
	Crop*Fert	2	0.90	0.12	0.8841
	Crop*Den	2	116.66	16.06	0.0001
	Fert*Den	4	21.63	1.49	0.2274
	C*Fert*Den	4	11.29	0.78	0.5467
	Error	34	132.49		
3rd	Crop	1	11682.0	1183.2	0.0001
	Fert	2	96.4	3.4	0.0444
	Den	2	3304.3	117.2	0.0001
	Block	2	91.4	1.0	0.3870
	Crop*Fert	2	27.5	3.1	0.0566
	Crop*Den	2	967.4	34.3	0.0001
	Fert*Den	4	177.7	3.2	0.0263
	C*Fert*Den	4	106.3	1.9	0.1357
	Error	34	479.4		

Table 4.3.2-1 continued

Harvest	Source	DF	Sum of squares	F	P_{HO}
4th	Crop	1	62227.6	1258.5	0.0001
	Fert	2	2652.1	26.8	0.0001
	Den	2	5408.1	54.7	0.0001
	Block	2	233.9	2.4	0.1092
	Crop*Fert	2	1796.1	18.2	0.0001
	Crop*Den	2	564.0	5.7	0.0073
	Fert*Den	4	67.8	0.3	0.8470
	C*Fert*Den	4	75.7	0.4	0.8193
	Error	34	1681.1		
5th	Crop	1	81493.3	1864.4	0.0001
	Fert	2	4210.8	48.2	0.0001
	Den	2	8919.8	102.0	0.0001
	Block	2	145.6	1.7	0.2042
	Crop*Fert	2	2594.7	29.7	0.0001
	Crop*Den	2	295.7	3.4	0.0457
	Fert*Den	4	14.8	0.1	0.9865
	C*Fert*Den	4	152.9	0.9	0.4893
	Error	34	1486.1		
6th	Crop	1	78691.0	1584.7	0.0001
	Fert	2	4730.3	47.6	0.0001
	Den	2	11027.1	111.0	0.0001
	Block	2	178.5	1.8	0.1811
	Crop*Fert	2	1834.5	18.5	0.0001
	Crop*Den	2	96.9	1.0	0.3872
	Fert*Den	4	99.3	0.5	0.7360
	C*Fert*Den	4	198.3	1.0	0.4219
	Error	34	1688.3		

Table 4.3.2-1 continued

Harvest	Source	DF	Sum of squares	F	P_{HO}
7th	Crop	1	45263.7	579.8	0.0001
	Fert	2	6476.3	41.5	0.0001
	Den	2	17169.4	110.0	0.0001
	Block	2	323.8	2.1	0.1413
	Crop*Fert	2	1210.3	7.8	0.0017
	Crop*Den	2	110.9	0.7	0.4986
	Fert*Den	4	14.3	0.1	0.9959
	C*Fert*Den	4	460.9	1.5	0.2312
	Error	34	2654.4		

By the second harvest (15 days after germination), dry matter in rape exceeded that shown by lupin (Fig 4.3.2-1). Comparison at different planting densities within lupin or within rape showed that although dry matter per unit area increased with planting density, the increase was not directly proportional to density. In general, mean yield at the mid density treatment was much closer to that of the high density treatment, at all harvests (Fig 4.3.2-1). At the 6th harvest ($LSD_{0.05}$ = 6.75 g/pot) and the final harvest ($LSD_{0.05}$ = 8.47 g/pot), the rape dry matter yield of the medium density treatment was statistically similar to that at the high density treatment, but differed significantly from that at the low density treatment (Fig 4.3.2-1).

Comparison of the effect of nitrogen fertilizer levels within crops showed that from the 3rd to the 5th harvest only rape responded positively to addition of nitrogen. At the 6th and 7th harvests, the dry matter yield of both crops was elevated by addition of nitrogen.

As observed with planting density, dry matter accumulation per pot did not increase proportionally with increase in N fertilizer application. In both crops, the yield from the upper and mid fertilizer applications were more similar to one another than to the lowest level. In rape, yields at the final harvest differed from one another at all fertilizer levels whereas yield of lupin at the lowest fertilizer was only significantly different from yield at the other levels.

In weight on average, lupin seed is 73 times heavier than rape seed. At the first harvest (8 days) from sowing, this was reflected in dry matter of lupin being 4.4 times greater than rape on average at all densities (Fig 4.3.2-3). By the second harvest this situation was reversed, rape having overtaken lupin, yield per unit area remaining in proportion to density (Fig 4.3.2-4).

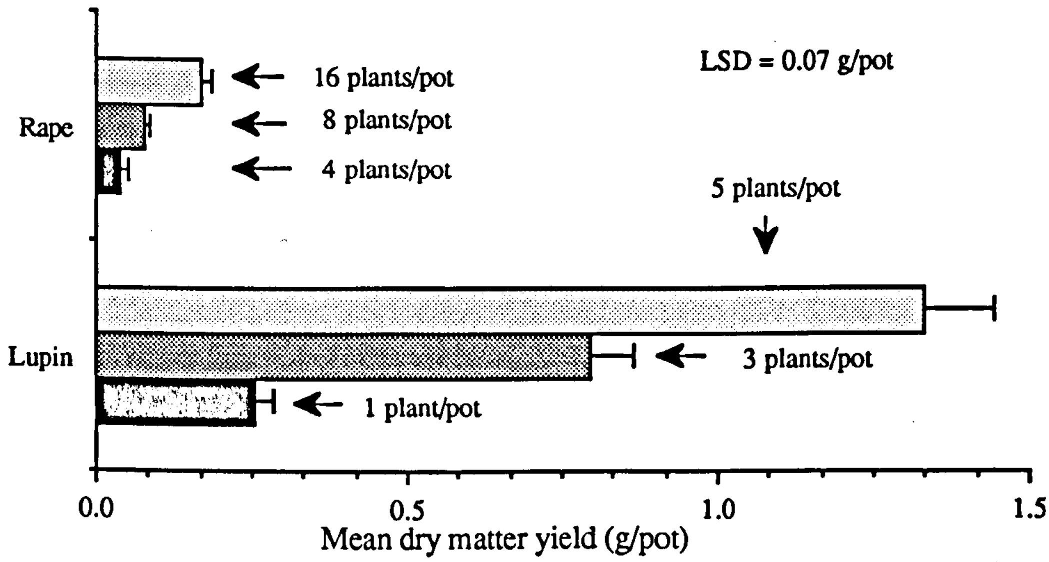


Fig 4.3.2-3. Comparison of dry matter (above + below ground) of lupin and rape, 8 days after sowing, pooled data over N fertilizer application (experiment PE290). Confidence limits are standard errors of the mean.

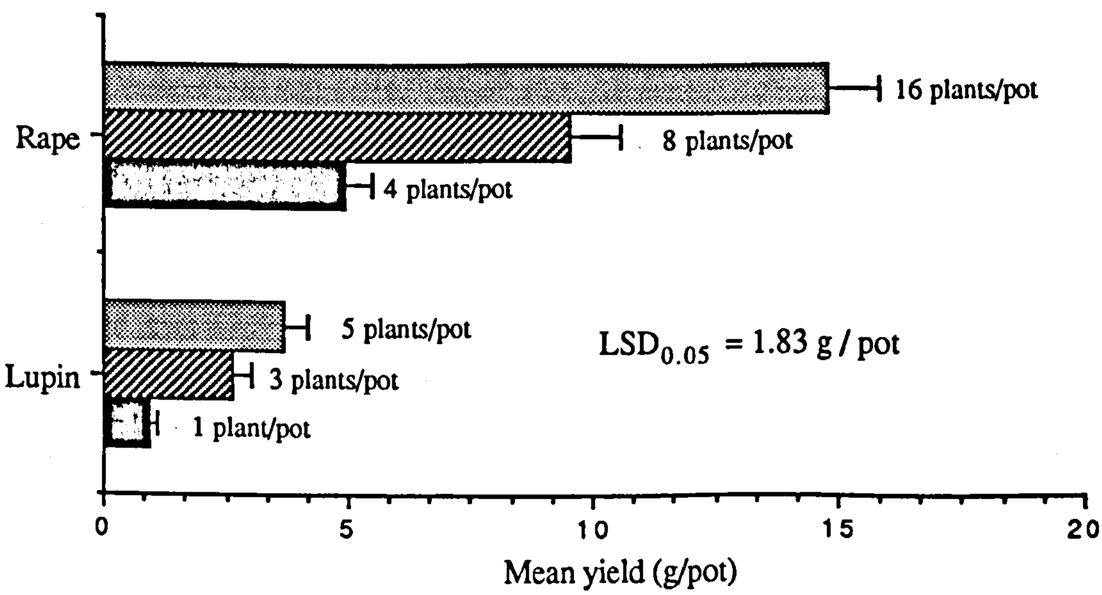


Fig 4.3.2-4. Comparison of dry matter (above + below ground) of lupin and rape, 23 days after sowing, pooled data over N fertilizer application (experiment PE290). Confidence limits are standard errors of the mean.

Statistical analysis showed that seed yield of the two crops was also significantly different ($p < 0.01$) and significantly affected by planting density ($p < 0.01$) and fertilizer N application ($p < 0.01$) (Table 4.3.2-3), as was root biomass (Table 4.3.2-4).

Table 4.3.2-3. Analysis of variance of seed yield of lupin and rape at the final harvest (experiment PE290). C = crop, N = nitrogen fertilizer, D = density.

Source	DF	Sum of squares	F	P_{HO}
Crop	1	61.44	23.52	0.0001
Fertilizer	2	253.96	48.61	0.0001
Density	2	980.08	187.60	0.0001
Block	2	5.02	0.96	0.3926
C*N	2	5.94	1.14	0.3326
C*D	2	97.09	18.58	0.0001
N*D	4	15.94	1.53	0.2168
C*N*D	4	29.38	2.81	0.0406
Error	34	88.81		
Total	53	1537.65		

Table 4.3.2-4. Analysis of variance of root biomass of lupin and rape at the final harvest (experiment PE290). C = crop, N = nitrogen fertilizer, D = density.

Source	DF	Sum of squares	F	P_{HO}
Crop	1	2171.5	789.92	0.0001
Fertilizer	2	207.3	19.51	0.0001
Density	2	376.4	68.45	0.0001
Block	2	0.2	0.04	0.9602
C*N	2	9.5	1.73	0.1925
C*D	2	92.2	16.77	0.0001
N*D	4	70.8	6.44	0.0006
C*N*D	4	111.3	10.12	0.0001
Error	34	93.5		
Total	53	3032.6		

A conspicuous common feature of both analysis was a significant three way interaction term amongst crop, density and fertilizer level. The corresponding analysis of variance for above ground biomass at the final harvest is given in Table 4.3.2-5.

Table 4.3.2-5. Analysis of variance of above ground biomass of lupin and rape at the final harvest (experiment PE290). C = crop, N = nitrogen fertilizer, D = density.

Source	DF	Sum of squares	F	P_{HO}
Crop	1	27607	376.4	0.0001
Fertilizer	2	4918	33.5	0.0001
Density	2	12471	85.0	0.0001
Block	2	318	2.2	0.1297
C*N	2	1156	7.9	0.0015
C*D	2	96	0.6	0.5270
N*D	4	62	0.2	0.9302
C*N*D	4	229	0.8	0.5464
Error	34	2494		
Total	53	49351		

Fig 4.3.2-5 compares the relative yield responses in relation to fertilizer and density of the two crops. The significant three way interaction terms arise because the yield response surface across fertilizer and density differ between lupin and rape. This comparison is in part artificial since the fertilizer levels and densities were not identical for both crops. Nevertheless it is clear to see that there was a tendency for lupin to respond to increasing density and fertilizer to a greater extent than rape for both seed yield and root biomass. But the three way interaction for the above ground biomass was not significant ($p > 0.05$, Table 4.3.2-5).

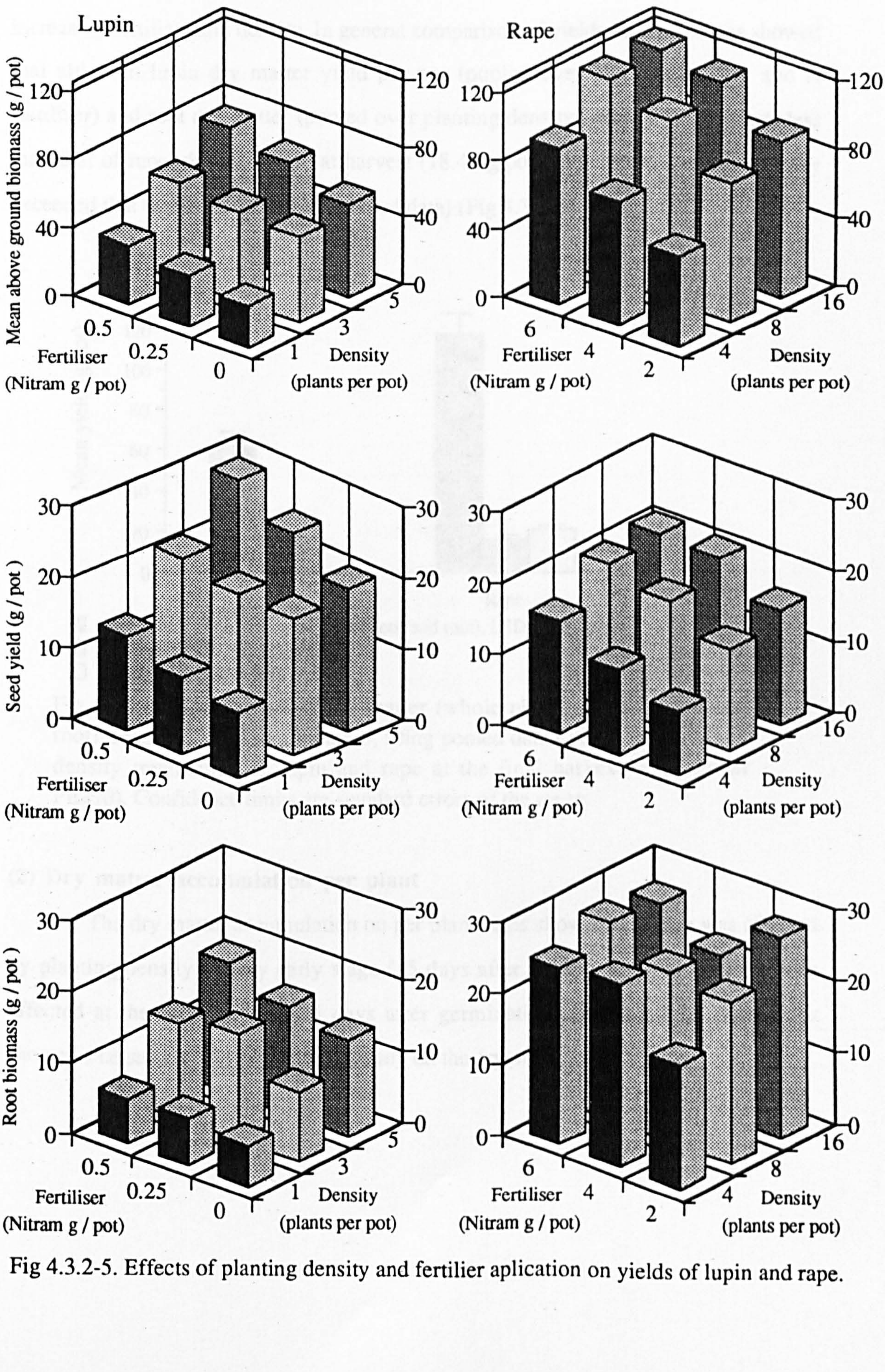


Fig 4.3.2-5. Effects of planting density and fertilier aplication on yields of lupin and rape.

Of the two crops, rape was the least responsive in root biomass per pot to increasing fertilizer and density. In general comparison of yields between crops showed that although lupin dry matter yield per pot (pooled over planting density and N fertilizer) and root dry matter (pooled over planting density and N fertilizer) was less than that of rape, the seed yield at harvest (18.46 g/pot, pooled data) was marginally exceeded that of rape (16.33 g/pot, pooled data) (Fig 4.3.2-6).

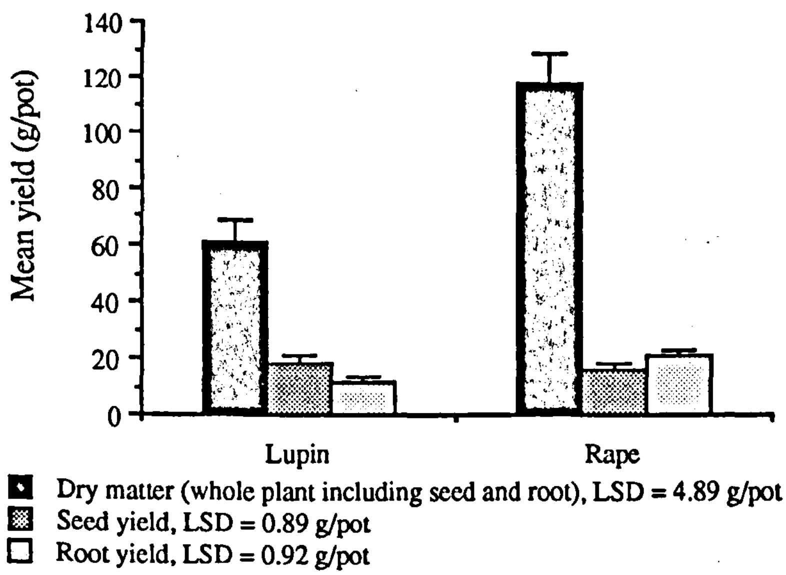


Fig 4.3.2-6. Comparison of dry matter (whole plant including seed and root), seed yield and root biomass, using pooled data over N fertilizer and density treatments, of lupin and rape at the final harvest (experiment PE290). Confidence limits are standard errors of the mean.

(2) Dry matter accumulation per plant

The dry matter accumulation on per plant basis showed that rape was affected by planting density at very early stage (15 days after germination) whilst lupin was affected at the third harvest (45 days after germination) (Fig 4.3.2-7). Both crops showed a negative effect of planting density on the dry matter accumulation.

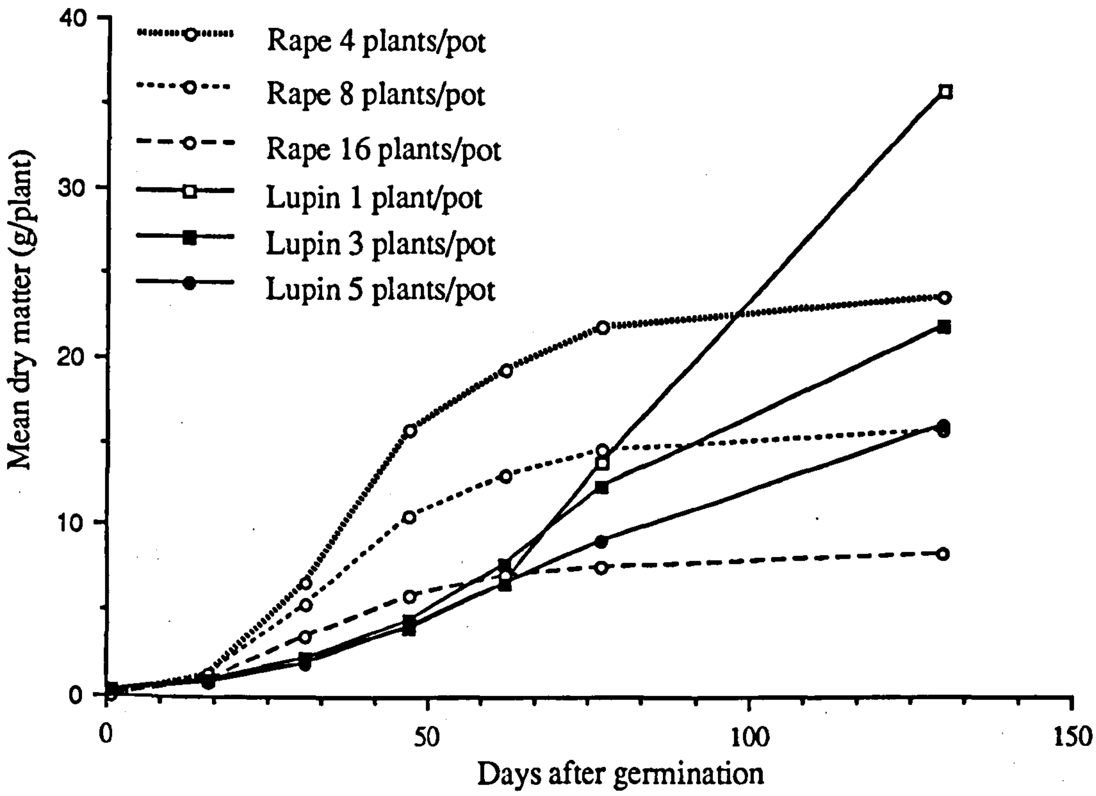


Fig 4.3.2-7. Effects of planting density on the dry matter accumulation per plant of lupin and rape, pooled data over N fertilizer application (experiment PE290).

The effects of nitrogen fertilizer on the dry matter accumulation on per plant basis of the crops were similar to those on per unit area basis, but the rape yields were lower than lupin at the final harvest (Fig 4.3.2-8).

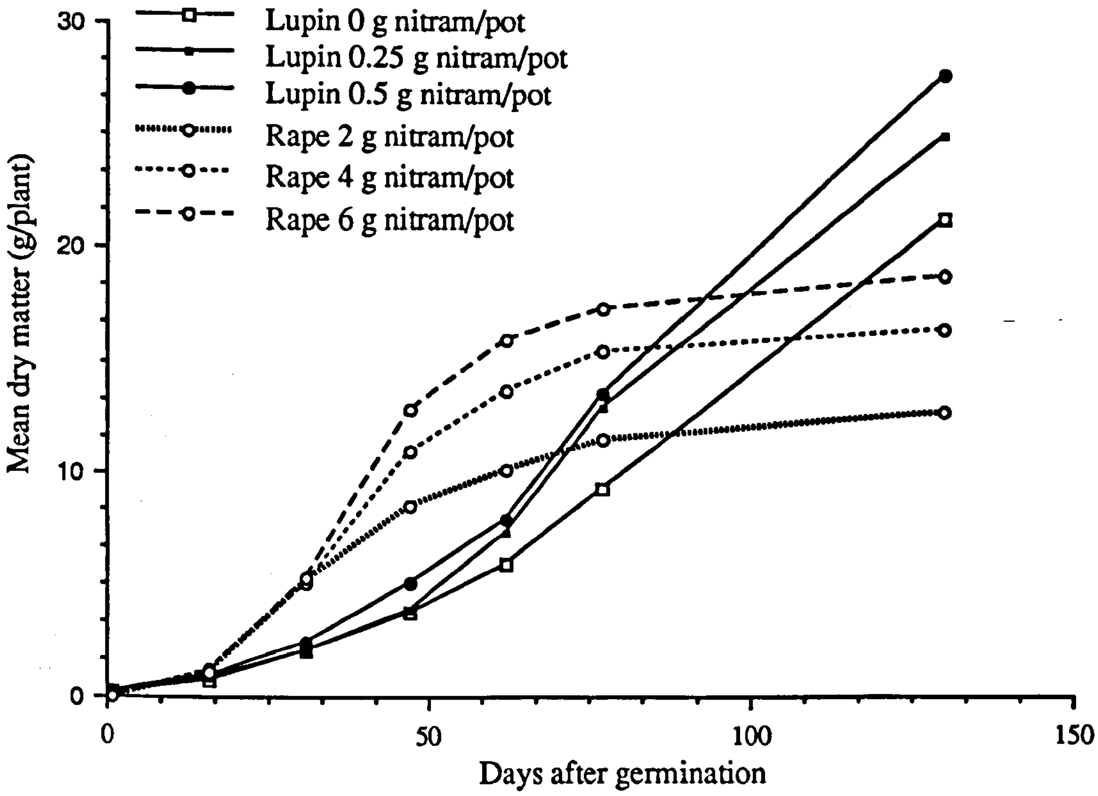


Fig 4.3.2-8. Effects of nitrogen fertilizer on the dry matter accumulation per plant of lupin and rape, using pooled data over planting density (experiment PE290).

(3) Relative growth rate

In this experiment, a long leaf duration paralleled with flowering and seed filling was observed in lupin whilst rape leaves dropped at pod development stage.

Analysis of relative growth rate indicated major differences between the two crops. The relative growth rate of rape was much higher than that of lupin over the first 30 days of growth after germination but decreased rapidly and was less than that of lupin for the remainder of the season. Lupin in contrast maintained relatively lower growth rate than rape with a much lower rate of decline over the growing period (Fig 4.3.2-9).

The effects of density and nitrogen application rate on relative growth rate are illustrated in Figs 4.3.2-10 and 11.

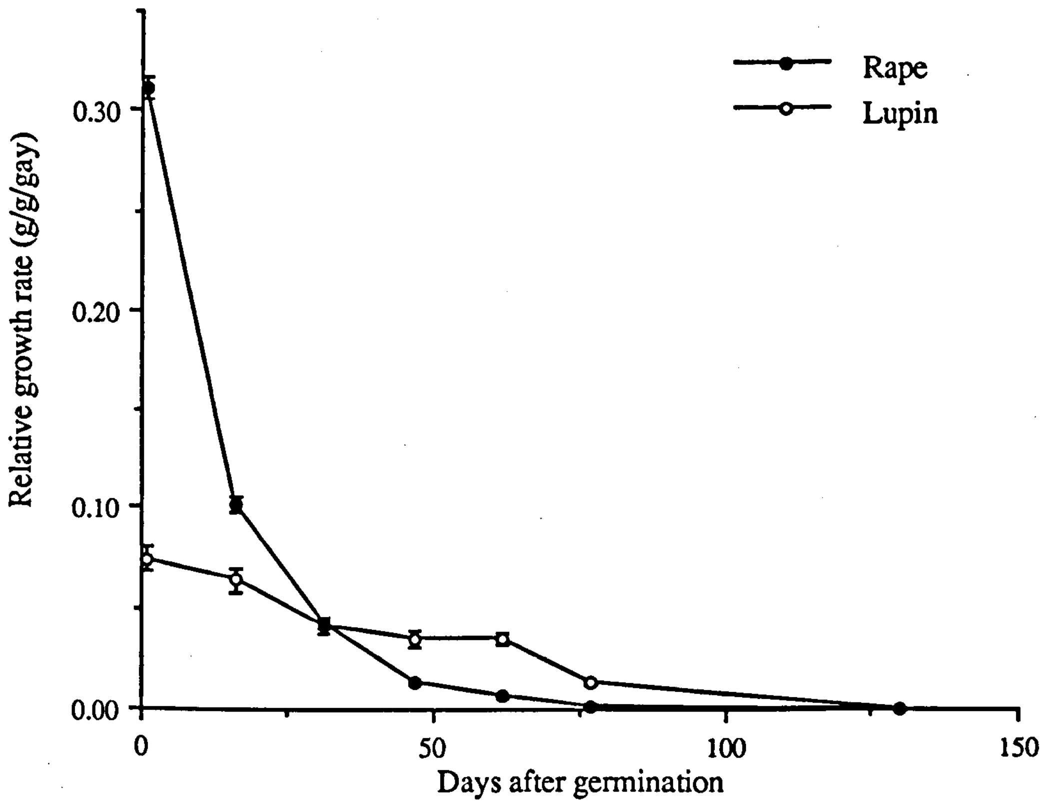


Fig 4.3.2-9. Comparison of relative growth rate of lupin and rape, using pooled data over N fertilizer application and planting density (experiment PE290). Confidence limits are standard errors of the mean.

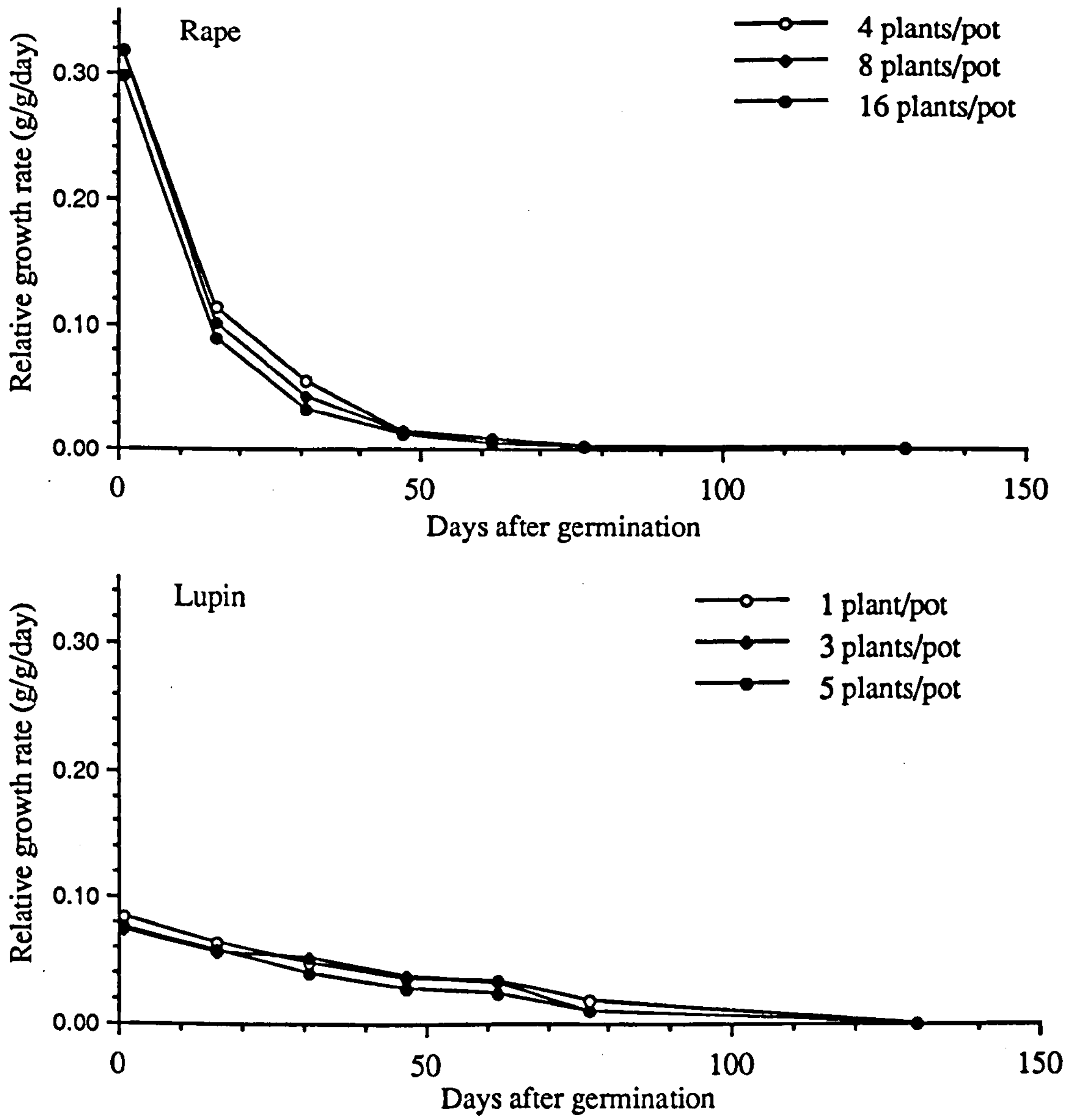


Fig 4.3.2-10. Effects of planting density on the relative growth rate of rape and lupin, pooled data over N fertilizer application (experiment PE290).

Fig 4.3.2-10 illustrated that planting density affected ($p < 0.01$) the relative growth rate of rape from 30 days to 60 days after germination, but affected ($p < 0.01$) that of lupin over a longer period (Appendix C, Table C-3 for analysis of variance).

The effects of N fertilizer application on the dry matter accumulation of the two crops were also reflected in the relative growth rate (Fig 4.3.2-11).

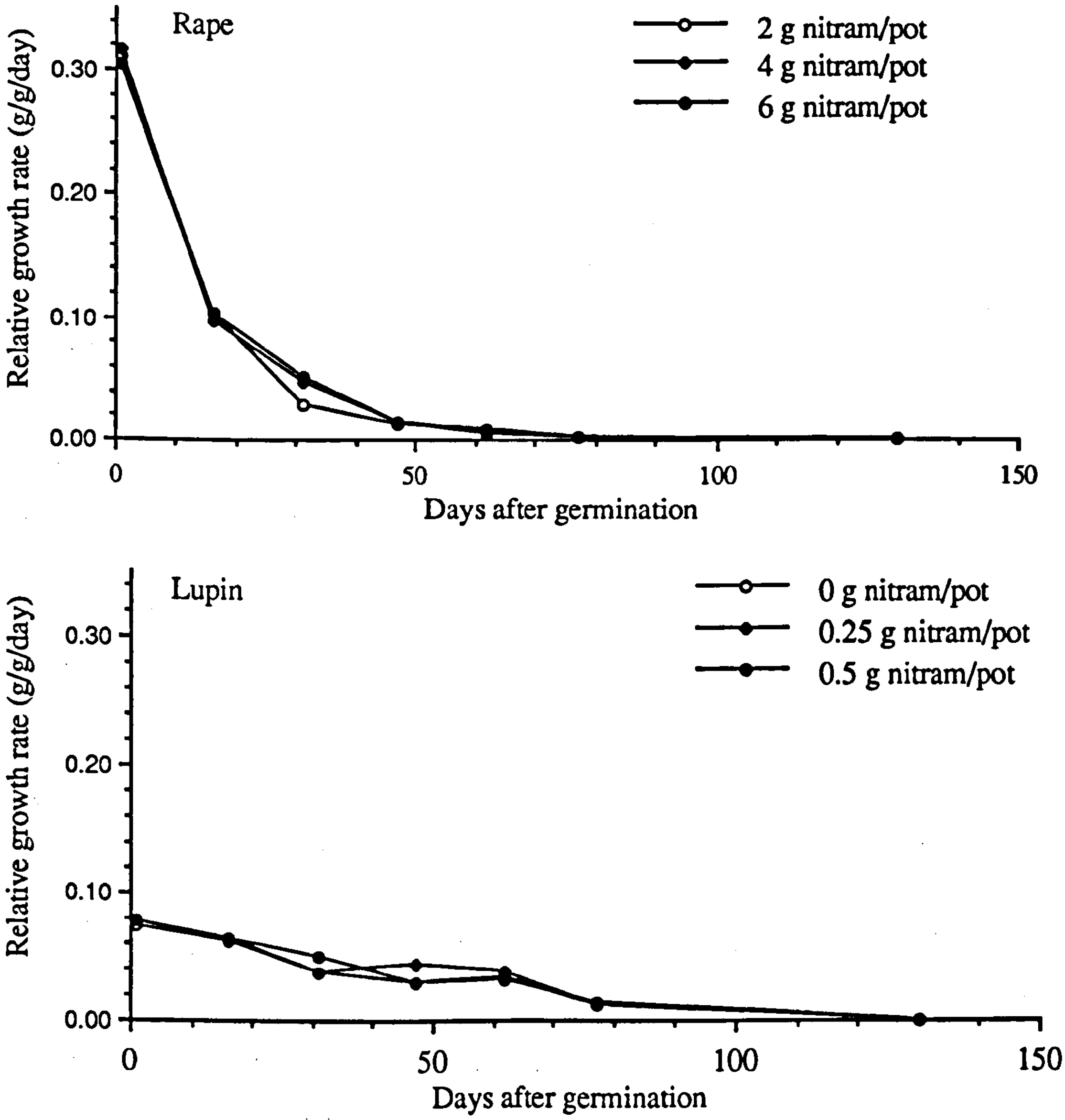


Fig 4.3.2-11. Effects of N fertilizer application on the relative growth rate of rape and lupin, pooled data over planting density (experiment PE290).

Fig 4.3.2-11 indicated that nitrogen fertilizer affected ($p < 0.01$, Appendix C, Table C-3 for analysis of variance) the relative growth rate of rape from 15 days to 45 days after germination but did not affect that of lupin (LSD = 0.013).

(3) Fate of nitrogen

Nitrogen accumulation per unit area

Analysis of variance (Table 4.3.2-6) of nitrogen accumulation between treatments showed that crops accumulated different amounts of nitrogen ($p < 0.01$), and density, N fertilizer application level and blocks had a significant effect on the nitrogen accumulation ($p < 0.01$). It also indicated that a significant interaction between crop and fertilizer level ($P < 0.01$). Table 4.3.2-6 (between harvest effects) suggested that the amount of N accumulated over time, in crops at each harvest were significantly different ($p < 0.01$), and varied according to N fertilizer level and density treatments ($p < 0.01$). Figs 4.3.2-12 and 13 show the patterns of nitrogen accumulation for the two crops in relation to planting density and nitrogen application. In general lupin exhibited a consistent increase in nitrogen accumulation in biomass over the growth period whereas in rape a maximum cumulative nitrogen content was found 62 days after germination. The absolute amount of N accumulated in biomass per pot fell in relation to density of planting and nitrogen application level, the higher the density or nitrogen application the higher the N accumulation, in both crops. In rape 62 days after germination at peak N content, at least twice as much N was present in biomass as in lupin but this declined rapidly by the 6th harvest to then accumulate slowly to amounts comparable with that in lupin at the conclusion of the experiment.

Table 4.3.2-6. Analysis of variance of nitrogen accumulation between harvests (time) of lupin and rape (experiment PE290). C = crop, N = nitrogen fertilizer, D = density.

Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	1	18.52	966.51	0.0001
Density	2	9.31	242.97	0.0001
Fertilizer	2	5.61	146.43	0.0001
Block	2	0.30	7.89	0.0015
C*D	2	0.01	0.27	0.7675
C*N	2	2.21	57.53	0.0001
N*D	4	0.20	2.66	0.0493
C*N*D	4	0.10	1.29	0.2945
Error	34	0.65		

Between harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	6	71.37	555.70	0.0001
Harvest*C	6	32.22	235.30	0.0001
Harvest*N	12	4.12	16.05	0.0001
Harvest*D	12	3.97	15.46	0.0001
Harvest*C*N	12	4.13	16.09	0.0001
Harvest*C*D	12	1.56	6.07	0.0002
Harvest*N*D	24	0.91	1.77	0.0950
Harvest*C*N*D	24	0.87	1.69	0.1116
Error(harvest)	204	4.37		

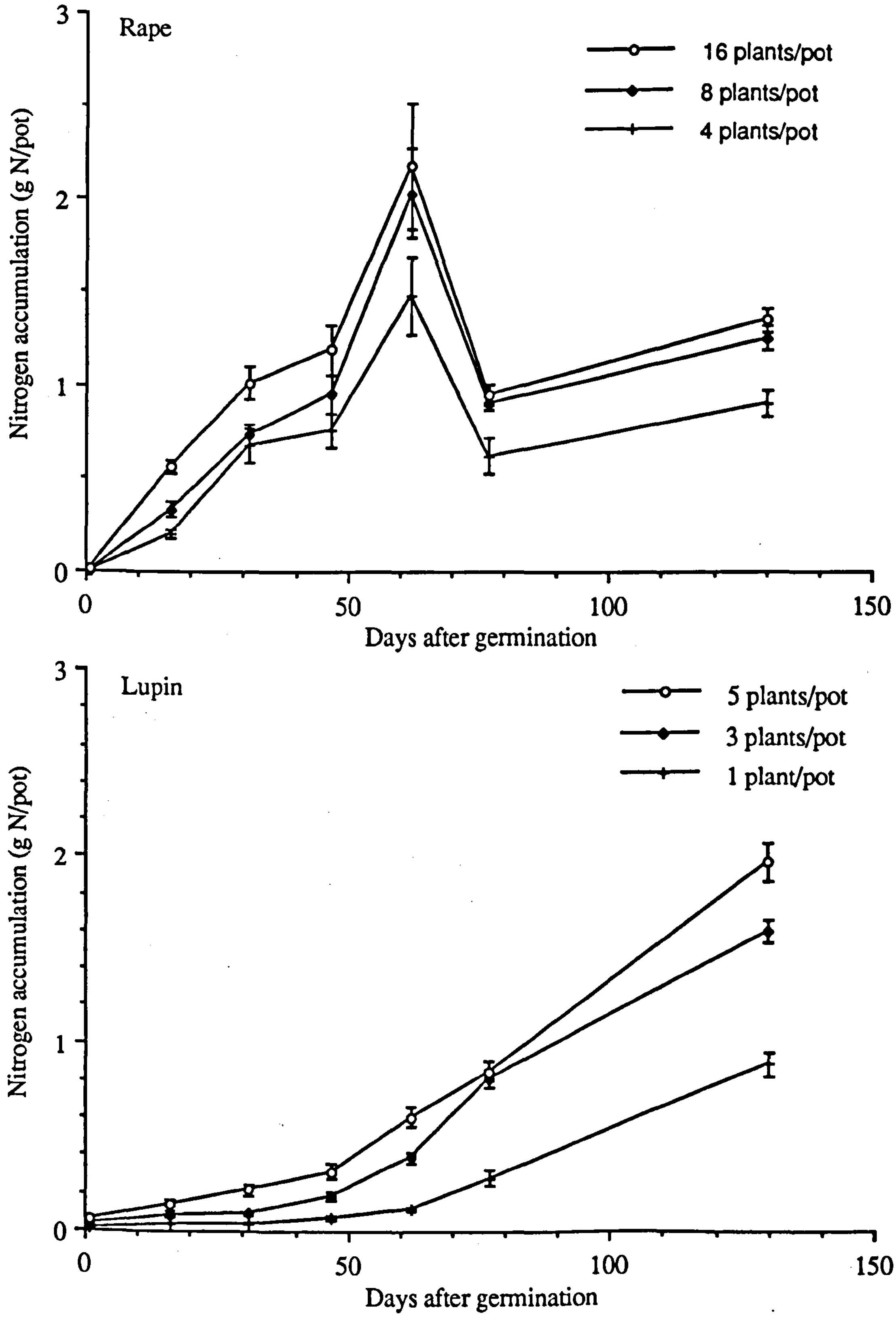


Fig 4.3.2-12. Effects of time (harvest) and planting density on the nitrogen accumulation (in above + below ground dry matter) of the two crops, using pooled data over N fertilizer application (experiment PE290). Confidence limits are standard errors of the mean.

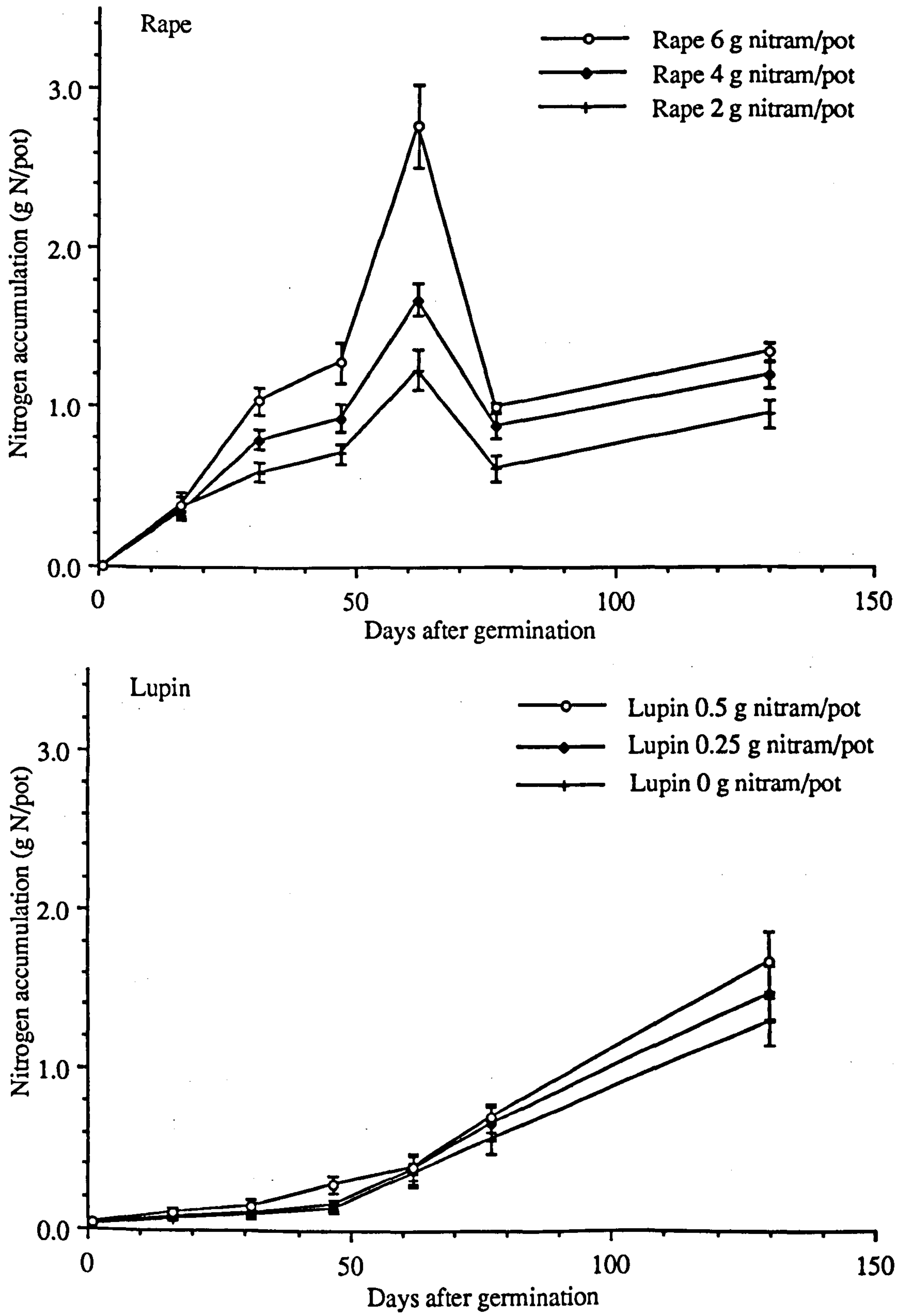


Fig 4.3.2-13. Effects of time (harvest) and N fertilizer application on the nitrogen accumulation (in above + below ground dry matter) of the two crops, using pooled data over planting density (experiment PE290). Confidence limits are standard errors of the mean.

Changes in total soil nitrogen

The main source of soil nitrogen is derived from the soil organic matter from which nitrogen is released as soil organic matter is mineralized. Soil total nitrogen in context of this study, therefore, is defined as nitrogen in soil organic matter.

Analysis of variance (Table 4.3.2-7) suggested that none of the individual treatments caused a significant ($p > 0.05$) effect when considered alone. However the total nitrogen (%) content of the soil prior to use contained significantly more N than the soil at the conclusion of the experiment ($p < 0.01$). A significant harvest crops interaction arose as a consequence of a lowering of total soil nitrogen to a greater extent under rape than lupin (Fig 4.3.2-14).

Table 4.3.2-7. Analysis of variance of total nitrogen (%) in soil before and after (time) the experiment (PE290). C = crop, N = nitrogen fertilizer, D = density.

Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	1	0.00062	3.39	0.0744
Density	2	0.00019	0.52	0.5973
Fertilizer	2	0.00002	0.05	0.9471
Block	2	0.00035	0.94	0.3993
C*D	2	0.00025	0.69	0.5104
C*N	2	0.00004	0.11	0.8927
N*D	4	0.00034	0.46	0.7625
C*N*D	4	0.00044	0.60	0.6627
Error	34	0.00625		

Between harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	1	0.006496	54.55	0.0001
Harvest*C	1	0.001964	16.49	0.0003
Harvest*N	2	0.000437	1.79	0.1817
Harvest*D	2	0.000018	0.07	0.9283
Harvest*block	2	0.000617	2.59	0.0898
Harvest*C*N	2	0.000042	0.18	0.8396
Harvest*C*D	2	0.000047	0.20	0.8208
Harvest*N*D	4	0.000326	0.68	0.6084
Harvest*C*N*D	4	0.000115	0.24	0.9126
Error (harvest)	34	0.004049		

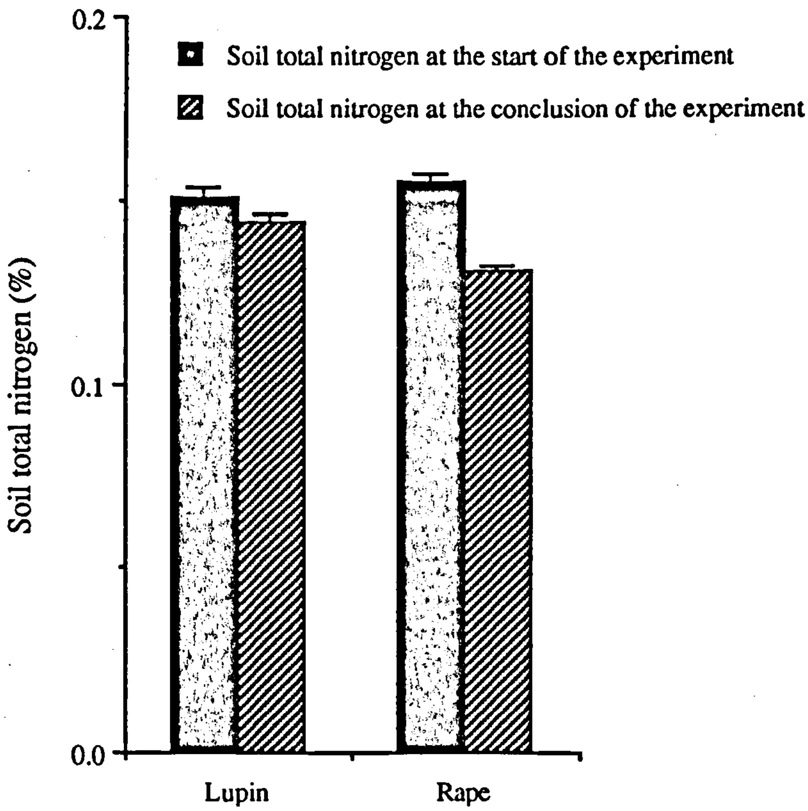


Fig 4.3.2-14. Comparison of soil total nitrogen content (%) before and after the experiment (PE290), using pooled data over N fertilizer and density treatments. Confidence limits are standard errors of the mean.

Changes in extractable soil nitrogen

The available nitrogen as a plant nutrient in soil is mainly in the form of nitrate and ammonium nitrogen, which may be considered as extractable nitrogen (mg N/100 g soil).

Analysis of variance of soil extractable nitrogen (Table 4.3.2-8) indicated that, effects of main treatment factors of crop and density and the interaction between crop and density were not apparent ($p > 0.05$). But N fertilizer treatment had a significant effect on the extractable nitrogen in soil, and as did interactions between crop and fertilizer and between fertilizer and density ($p < 0.05$). There was also a significant interaction amongst crop, fertilizer and density.

The statistical analysis also indicated that extractable nitrogen changed significantly with time of harvest ($p < 0.01$). Crop type altered the amount of extractable N over time ($p \leq 0.05$) and there were significant interactions between crop and fertilizer over harvests. Significant differences occurred amongst blocks over time also ($0.01 < p < 0.05$).

Table 4.3.2-8. Analysis of variance of extractable nitrogen (mg N/100 g soil) in soil at each harvest (experiment PE290). C = crop, N = nitrogen fertilizer, D = density.

Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	1	1.48	2.46	0.1259
Density	2	0.07	0.06	0.9433
Fertilizer	2	12.93	10.71	0.0002
Block	2	5.08	4.21	0.0233
C*D	2	0.24	0.20	0.8181
C*N	2	6.07	5.03	0.0122
N*D	4	13.46	5.57	0.0015
C*N*D	4	8.30	3.44	0.0183
Error	34	20.52		

Between harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	6	2199.57	4588.74	0.0001
Harvest*C	6	15.80	3.30	0.0491
Harvest*N	12	23.76	2.48	0.0597
Harvest*D	12	5.27	0.55	0.6804
Harvest*block	12	35.85	3.74	0.0112
Harvest*C*N	12	31.32	3.27	0.0209
Harvest*C*D	12	10.13	1.06	0.3817
Harvest*N*D	24	36.97	1.93	0.0792
Harvest*C*N*D	24	33.16	1.73	0.1176
Error (harvest)	204	162.97		

Fig 4.3.2-15 shows that a significant loss of extractable nitrogen occurred during the first 30 days of growth and that crops influenced the level of extractable nitrogen up to 50 days after germination. Their scale of the influence was much less than the over-riding effects of time.

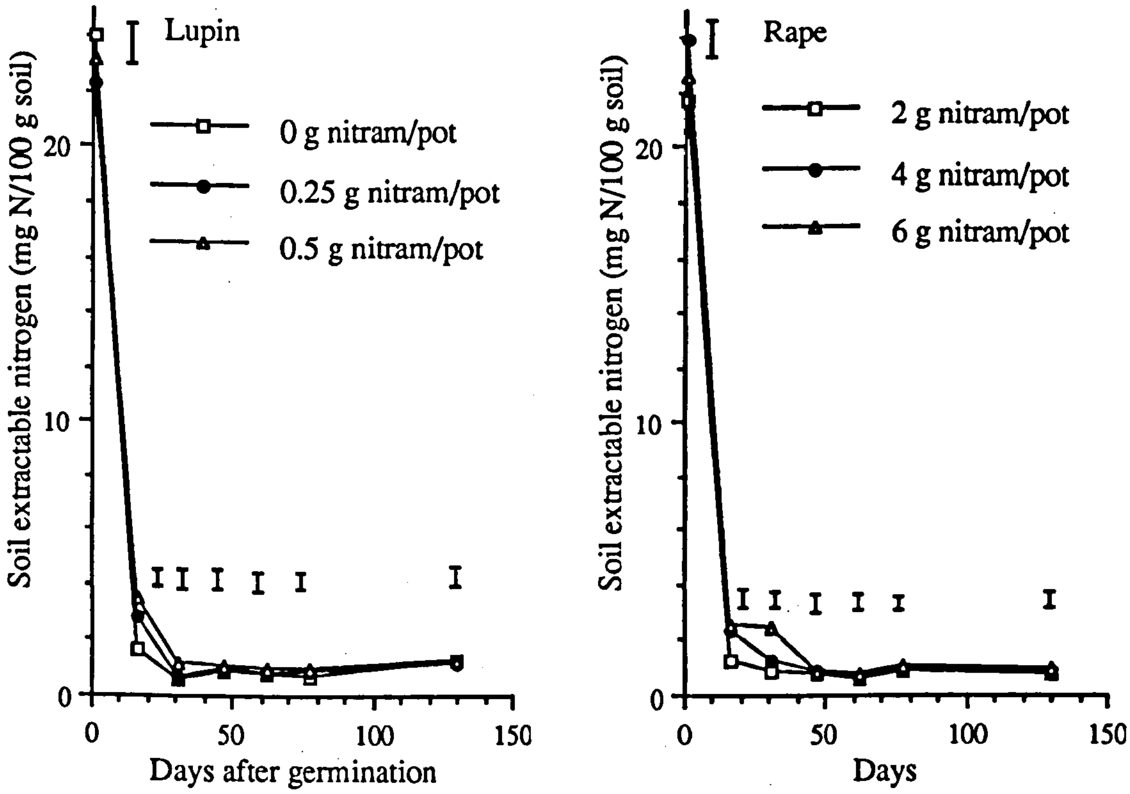
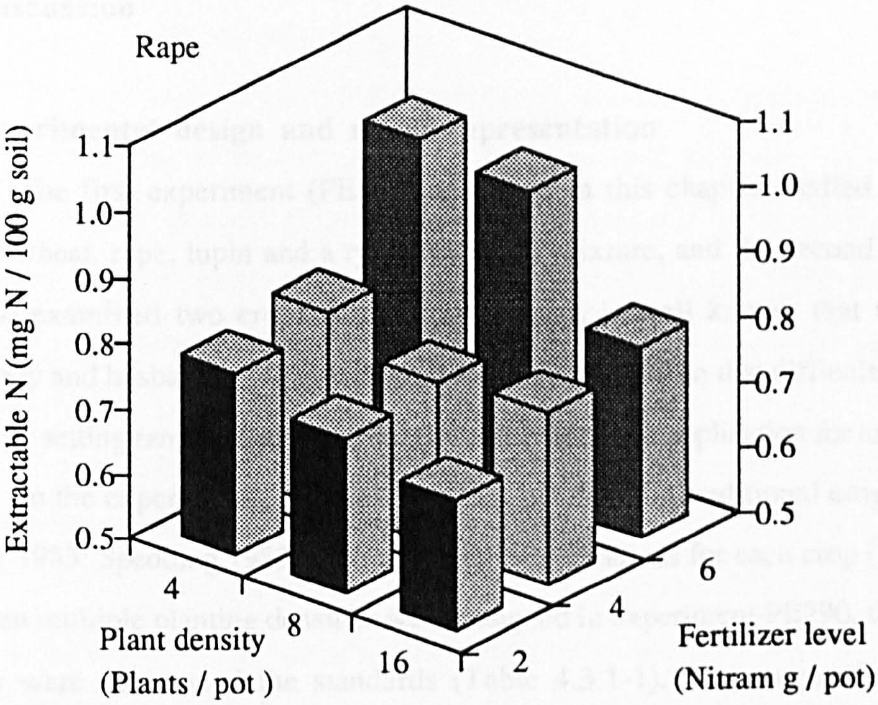


Fig 4.3.2-16. The effect of N fertilizer application level on the soil extractable nitrogen (mg/100 g soil) over time for two crops, using pooled data over planting density (experiment PE290). Confidence limits are standard errors of the mean. Soil extractable nitrogen is defined as NO_3-N + NH_4-N per 100 g of soil.

Extractable soil nitrogen levels were however dependent upon the interaction of planting density and nitrogen fertilizer level. This interaction developed over time and was evident by the fourth harvest being maintained until final harvest. Fig 4.3.2-17 illustrates the form of this relationship at this time. In rape in most treatment combinations, extractable nitrogen diminished with increasing density and conversely increased with addition of fertilizer. However at the highest fertilizer level at planting densities of 4 and 8 plants per pot extractable nitrogen levels were similar, 0.38 mg N/100 g soil. Conversely in lupin whereas increasing density of plants diminished extractable nitrogen at 0 and 5 g nitrogen application rates, there was no corresponding decline at the intermediate level of 0.25 g nitram per pot.



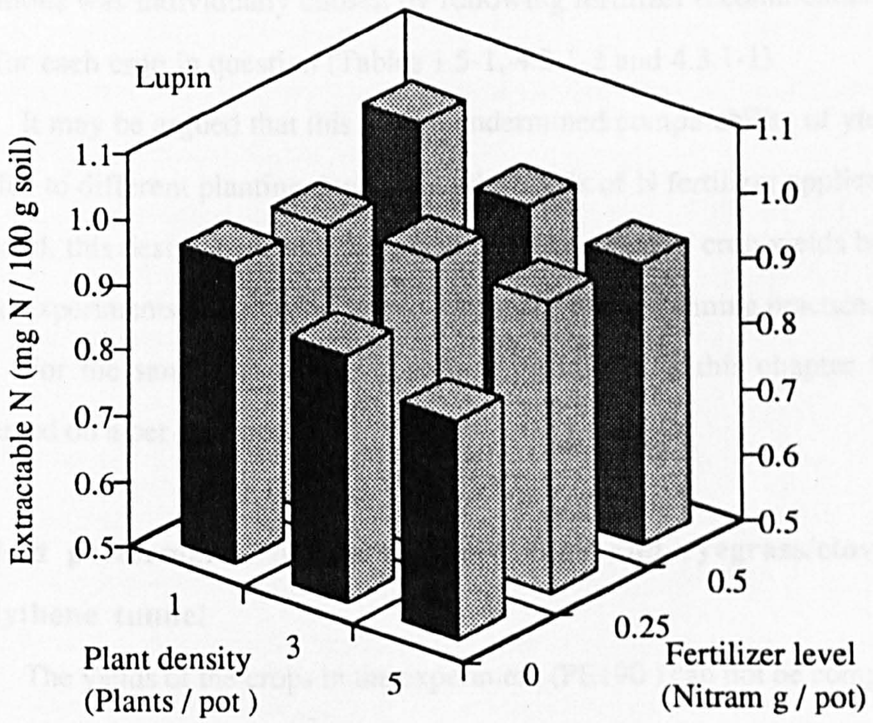


Fig 4.3.2-17. The influence of N fertilizer level, planting density and crop on the soil extractable nitrogen content (mg N / 100 g soil), data from the 4th harvest (experiment PE290).

4.4 Discussion

(1) Experimental design and result representation

The first experiment (PE190) described in this chapter studied four crops, namely wheat, rape, lupin and a ryegrass/clover mixture, and the second experiment (PE290) examined two crops (lupin and rape). It is well known that the growth, phenology and husbandry of these crops differ considerably so that difficulties arose for uniformly setting ranges of planting density and N fertilizer application for each crop.

In the experiments, planting densities practiced in traditional crop husbandry (Harper 1983; Spedding 1983) were considered as standards for each crop (Table 4.2.1-1). When multiple planting densities were designed in experiment PE290, the ranges of density were set around the standards (Table 4.3.1-1). The range of N fertilizer applications was individually chosen by following fertilizer recommendations (MAFF 1983) for each crop in question (Tables 1.5-1, 4.2.1-2 and 4.3.1-1).

It may be argued that this design undermined comparability of yields between crops due to different planting density and the levels of N fertilizer application. On the other hand, this design gave an assessment in comparison of crop yields being close to the field experiments described in previous chapters and to farming practice.

For the same reason, the experimental results in this chapter were mainly represented on a per unit area basis.

(2) Yield performance of wheat, lupin rape and ryegrass/clover mixture in polythene tunnel

The yields of the crops in the experiment (PE190) can not be compared directly with those in the field experiment. The economic yields of wheat (53.49 g/pot), lupin (53.36 g/pot), rape (43.5 g/pot) and the ryegrass/clover mixture (180.5 g/pot) were more than two fold greater than the average yield nationwide (MAFF, DAFS and MANI 1982, 1983 and 1984; Johnson 1981; Morrison , Jackson and Sparrow 1980). This is because not only were the growth conditions (temperature and water supply etc) favorable but also pot area (edge effect) although canes and strings were used to prevent them from over shade beyond the pot.

The seed yields of lupin (18.46 g/pot) and rape (16.33 g/pot) in the experiment (PE290) were close to the average yields from the field experiments (F1EX89 and F2EX91) but less than half of those from the experiment (PE190) although a similar experimental environment (polythene tunnel) was used. The low seed yield may have been caused by later sowing (May) and low temperature during the seed ripening (October).

The ranking of economic yield amongst the crops, however, followed the same order as observed in the field experiments described in previous chapters, the highest yield being in the ryegrass/clover mixture, lowest in rape and with wheat intermediate, except for lupin seed yield which was surprisingly almost as high as wheat. This unusual performance of lupin may suggest a high potential yielding capacity under the favorable environment artificially created in the polythene tunnel. An alternative explanation may be that the densities employed were spuriously lowered since the leaves of lupin extended beyond the pot area.

The advantages of a long growing period and 100% harvest index in the ryegrass/clover mixture ensured that this crop achieved the highest rank and could be clearly outlined since it accumulated almost the same dry matter as rape (Fig 4.2.2-4).

(3) Patterns of dry matter accumulation of the crops

The pattern of dry matter accumulation of the four crops fell into two basic types. In rape and wheat, dry matter was rapidly accumulated during vegetative growth until flowering and slowly increased at the later seed filling stage. Although different patterns of dry matter accumulation in rape cultivars were observed by Munir (1982), the basic pattern was similar, and so was that in wheat (Jadhav 1989). Unlike rape and wheat, lupin and the ryegrass/clover mixture accumulated dry matter steadily as plant age increased. In lupin, leaves dropped at the final harvest but the leaf duration was longer than rape. It seems that the drop of the leaves in lupin did not apparently reduce the whole plant dry matter (Larson, Cassman and Phillips 1989). This may be the result of active photosynthesis of stem and pod during the seed filling stage, which may compensate for the dry matter of the fallen leaves.

The pattern of dry matter accumulation in the ryegrass/clover mixture was mainly affected by the frequency of cuttings. Because of periodical cutting, some loss in interception of available light may occur so that a slow increase in dry matter or even a negative carbon balance may extend for up to three weeks and then be followed by a 'linear' phase of growth (Leafe 1978). Data for total dry matter represents the accumulation of biomass from each cutting and is likely to be linear with plant age if the temporal variability is small (Fig 4.2.2-1).

According to the pattern of dry matter accumulation, the growth pattern of rape could be clearly divided into stages of establishment and seedling growth (from 1st to 2nd harvest), rapid vegetative growth (from 2nd to 5th harvest), flowering and ripening (from 5th to 7th harvest), while the growth period of lupin could hardly be divided clearly into stages like rape (Fig 4.3.2-7 and Fig 4.3.2-8).

The pattern of dry matter accumulation illustrated that rape was a fast growing crop at very early growing stage and could accumulate a large amount of dry matter over a short period. This kind of growth pattern usually implies that a drought or failure in supply with large amount of nitrogen at vigorous vegetative growth stage may probably lead to a severe reduction of seed yield. In contrast, lupin grew relatively slowly but could accumulate dry matter over longer period. The growth pattern of lupin implies that lupin could more efficiently use the accumulated dry matter to form economic yield, which reflected a less dry matter yield but higher seed yield than rape.

(4) Patterns of nitrogen uptake by the crops

Nitrogen accumulation into biomass followed a similar pattern to dry matter increase, a close correlation being seen at the time of rapid growth in rape and wheat (10 to 80 days). A noticeable feature of total nitrogen incorporated into the plant material in rape and wheat was the considerable loss of accumulated nitrogen during the seed filling stage, 80 to 150 days in experiment PE190 (Fig 4.2.2-7). The amount of nitrogen accumulated in the plant material after flowering but subsequently appearing to be lost to the final grain product could be as high as 4.4 g N/pot (78.6 g N/m^2) on average (Fig 4.2.2-7). This represents 63.8% of the total accumulated nitrogen at the peak. The loss of accumulated nitrogen may result from the process of leaf drop and root decomposition coupled with inefficient translocation of leaf nitrogen to seed before final harvest although nitrogen is usually translocated from old leaves to young organs and seed when in limited supply (Ogunlela, Kullmann and Geisler 1990; Singh and Singh 1984). The nitrogen accumulation in rape was rarely reported in literature over the period 1983 - 1992.

Although the pattern of nitrogen accumulation in wheat suggested that wheat also lost nitrogen at the final harvest, the amount of accumulated nitrogen apparently lost was only 0.6 g/pot, being 21.4% of the total nitrogen accumulated at the peak. This pattern of nitrogen utilization does not always happen but has been observed by Darroch and Fowler (1990).

In contrast, lupin and the ryegrass/clover mixture accumulated nitrogen steadily with plant age and as dry matter increased. Although leaf drop in lupin was observed at seed maturity stage during the experiment, accumulated nitrogen loss was not apparent. This may be the result of effective nitrogen translocation from leaves to seed prior to leaf drop or active aerobic nitrogen fixation at seed maturity stage that compensated for the loss of nitrogen in leaves, or possibly both events happened. The pattern of nitrogen accumulation paralleled with dry matter increase in lupin (Figs 4.2.2-1 and 4.2.2-7) reported here was also observed by Larson, Cassman and Phillips (1989).

The pattern of nitrogen accumulation in the ryegrass/clover crop relates to the biological characteristics of the mixture. Cutting at regular intervals in the experiment removed the developing flower heads and truncated the phase of reproductive growth allowing further growth to occur through new tiller development. Thus the ryegrass/clover mixture repeatedly entered a new phase of vegetative growth. The harvested plant parts were the vegetative organs (leaves and stems) of the plant at a vigorous vegetative growth stage which did not involve any dead leaf material and hence nitrogen was accumulated effectively. Hunt (1973) and Leafe (1978) reported the similar patterns of nitrogen accumulation in this kind of crop mixture.

(4) Effects of N fertilizer and planting density on dry matter accumulation

The results from the two experiments reported here generally indicate that nitrogen stimulated dry matter accumulation and improved final economic yields. This function of nitrogen fertilizer as a plant nutrient is well documented (Cooke 1984). Nitrogen greatly stimulated the dry matter (DM) accumulation in rape (9.2 - 19.4 g DM/g nitram) and lupin (16.4 - 27.5 g DM/g nitram), but caused lesser increases in ryegrass/clover mixture (9.4 g DM/g nitram) and only 3.9 g DM/g nitram in wheat under the conditions of the experiment (PE190).

Rape accumulated the highest amount of nitrogen in the whole plant amongst the crops at the vegetative growth and flowering stages. But in whole plant material at the final harvest, rape exhibited almost the same amount as wheat and less than lupin and the ryegrass/clover mixture. At high levels of nitrogen fertilizer application, surplus uptake of nitrogen may occur in rape and would not appear to increase economic yield significantly (Kullmann and Geisler 1988).

The planting densities of rape in the experiment was in range from 71 - 286 plants/m^2 and this upper limit exceeded the normal target plant population of 200 plants/m^2 (Harper, 1983). The planting densities of lupin ranged from 18 - 89 plants/m^2 and spanned the normal target population of 23 - 40 plants/m^2 (Larson, Cassman and Phillips 1989). The increase of planting density generally increased the dry matter accumulation in rape and lupin and competition at high planting density was also observed (Fig 4.3.2-1). The similar effects of planting density on the dry matter accumulation in field condition was reported by Morrison, McVetty and Scarth (1990). The results from experiment (PE290) may suggest that 8 plants/pot for rape and 4 - 5 plants/pot for lupin were suitable for the pot experiment but these rates of plant population were not suitable for crop production in field experimentation since the edge effect was impossible to be quantified in the experiment reported here.

(5) Effects of crops on soil nitrogen content

The nitrogen assessment generally suggested that the crops significantly reduced total and extractable nitrogen content and the N fertilizer application elevated the extractable nitrogen in the soil. But the effects of the crops and N fertilizer were, unfortunately, weakened by unknown factors. For example in experiment PE190, the average extractable nitrogen content of the control (non-plant and non-N) treatment was reduced from 7.9 to 1.1 mg N/100 g soil during the experiment and that of the non-plant with 2 g N/pot applied declined from 25.0 to 1.2 mg N/100 g soil (Fig 4.2.2-9). The losses in those two treatment were certainly not affected by the crops. It is unclear, therefore, to what extent the extractable nitrogen in soil was affected by crops and to what extent it was affected by leaching or other factors. The effects of the crops and N fertilizer application on the extractable nitrogen in soil were small, < 0.6 mg N/100 g soil, in all cases. This may reflect the characteristics of the light soil used in the experiment. Harmsen and Kolenbrander (1965) reported that twice as much leaching occurred from light soils as from heavy soils hence low extractable nitrogen content being observed in light soil.

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CHAPTER 5 EFFECT OF CROP AND N FERTILIZER APPLICATION ON NITROGEN LEACHING

5.1 Introduction

In aerobic conditions, nitrogen fertilizer applied to soil is easily transformed to nitrate ions which are the most mobile form of nitrogen in most soils (Sprent 1987). This, highly soluble nitrate, is likely to be prone to leaching from the soil profile, especially under frequent rainfall and on well drained soil. Cooke (1967) cites strong evidence that nitrate, in a well drained soil, will ultimately be leached from the topsoil and subsoil if it is not taken up by plants and microbes or denitrified by bacteria. Further evidence for nitrogen leaching is that elevated nitrate concentrations may also be detected at a depth of 120 cm in soil profiles of arable fields (Ott, Hansen and Vogtmann 1983). Together with nitrogen in surface water runoff, nitrate ions leached from soil may enter running water courses nearby.

Previous research has revealed that, in some cases, as high as 10 - 25% of nitrogen fertilizer applied to soil may enter adjacent running water (Maitland 1984). Although, in most cases, phosphate initiates the qualitative and quantitative changes associated with eutrophication (Holt, Timmons and Latterell 1970), nitrate is more easily leached out of soil than phosphate (Holden 1976; Holden and Caines 1974), and is also an active element related with water body eutrophication. The costs of eutrophication of water bodies to human society, not to mention the ecological changes of flora and fauna, are obviously high in economic, environmental and recreational terms though they are sometimes difficult to evaluate (Arden-Clarke and Hodges 1988).

Leached nitrate ions may eventually reach groundwater reservoirs (Sprent 1987). On steady accumulation, this nitrate will cause groundwater contamination, which is likely to pose health risks to human populations. Recent studies have shown that leached nitrate has steadily accumulated in aquifers underlying persistently nitrogen fertilized agricultural land (Foster, Cripps and Smith-Carrington 1982). In the unsaturated zones of some aquifers below long-standing arable land in the eastern half of the U.K., the nitrate concentration has already exceeded the acceptable limits of World Health Organization criteria, which recommends the following limits for nitrate in drinking water : safe (< 11.3 mg NO_3-N/l), acceptable (11.3 - 22.6 mg NO_3-N/l) and unacceptable (> 22.6 mg NO_3-N/l) (Foster, Cripps and Smith-Carrington 1982).

Nitrate in drinking water is potentially toxic to humans, though its toxicity is not accurately quantified (Select Committee on The European Communities 1989). There are two likely health risks, methaemoglobinaemia in infants and carcinogenic effects on the adult human population (Anon 1978). Since groundwater from aquifers underlying extensive tracts of agricultural land provide some 30% of supplies of potable water in Britain (Foster, Cripps and Smith-Carrington 1982), nitrate levels in water in some areas in the U.K. pose a serious threat.

Recent studies of the nitrate profile in farming systems have revealed that the extent of fertilizer loss (N not utilized in crop growth) is usually in the range of 40 - 70% of fertilizer applied (Sprent 1987). This represents not only a potential pollution threat but also a considerable waste of money and resources. Thus it may be argued that eutrophication and groundwater contamination are probably the most serious problems associated with nitrogen fertilizer application in modern agricultural practice and may have major impacts on human society.

Studies on nitrate loss suggests that a wide range of factors influence the rates of nitrate leaching from agricultural soils. The most important of these are the nature of the soil, climate, cropping systems, patterns of nitrogen fertilizer application and farming operations. Because soil characteristics and climate are intrinsically uncontrollable, reduction of the risk of nitrate leaching will largely depend on the careful selection of cropping systems, changes in the pattern of nitrogen fertilizer usage and the methods of farming. For example, a number of studies have indicated that the widespread ploughing of grassland during the early 1940's provided the initial impetus for the rise in groundwater nitrate levels (Young 1986). The intensification of arable practices since then, with the accompanying increase in the use of inorganic nitrogen fertilizers, has reinforced and extended this trend. This implies that the nitrate leaching rate may be greatly influenced by the cropping systems and the patterns of fertilizer practice. In the same cropping system, either cereal production or grassland, the rate of nitrate leaching will mainly rely on farming methods (House, Stinner, Crossley and Odum 1984; White 1983; Ryden, Ball and Garwood 1984).

The results presented in the previous chapters indicated that the basic patterns of the plant growth, nitrogen uptake and response to nitrogen fertilizer of a cereal crop and the ryegrass/clover mixture are fundamentally different. How these differences associated with nitrogen fertilizer practice will affect the rate of nitrate leaching is unclear. This chapter describes a detailed examination of the effects of crops and nitrogen fertilizer application on nitrogen leaching under common climate and soil conditions.

5.2 Methods and Materials

Lysimeters were set up to examine the effects of three cropping regimes (barley, wheat and a ryegrass/clover mixture) and nitrogen fertilizer application on the leaching of nitrogen from the soil profile. The experiment was carried out continuously over the period from April 1989 to October 1991 in lysimeter pots. Each lysimeter comprised a cylinder 50 cm deep, the surface area being 730.5 cm^2. Initially, lysimeters were thoroughly cleaned, completely sealed with silicone rubber sealant and installed in a trench of soil supported by a retaining wall (Fig 5.2-1).

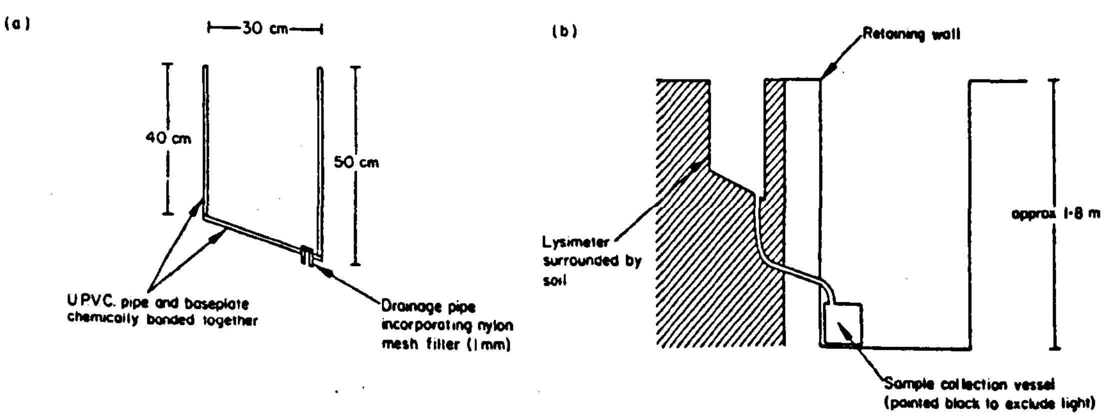

Fig 5.2-1. Cross-section of (a) the lysimeter, and (b) the lysimeter trench (from Marrs and Bradshaw 1980).

Connections between the drain-pipe and the lid of the drainage collection vessel were also sealed to prevent spoilage of samples. Each lysimeter was filled with three layers of soil (0 - 15 cm, 15 - 32 cm, 32 - 40 cm) from the field site so as to establish a soil profile similar to that of the field of the experimental site. Below 40 cm, a layer of sand (diameter of particle size from 1.5 mm to 2.5 mm) was placed inside at the base of each lysimeter to prevent the drainage pipes from being blocked by soil in natural drainage. To prohibit photobreakdown of nutrients in leachate, collection vessels were painted black and frequently emptied.

The experiment included 10 treatments with 3 replicates, utilizing 30 lysimeters. Initially barley and a ryegrass/clover mixture were sown on 15th April 1989, and in subsequent seasons those lysimeters sown with barley were sown to wheat on October 1989 and October 1990. The lysimeters containing the ryegrass/clover mixture, once sown, were retained till 13th October 1991. The experiment was coded as 'LEX89' for a period from April 1989 to October 1989, as 'LEX90' for the cropping year from October 1989 to October 1990 and as 'LEX91' from October 1990 to October 1991.

The experimental design was an unbalanced factorial completely randomized design. Barley or wheat was grown at 4 levels of nitrogen fertilizer application whilst the ryegrass/clover mixture was examined at 5 levels of nitrogen fertilizer application. Three lysimeter pots with no plants and no fertilizer addition were also included as a control.

To ensure sufficient supply of phosphate and potassium, 5.11 g (1 g/lysimeter = 136.9 kg/ha) of ICI No 12 fertilizer (N, P, K = 0, 8.73%, 26.56%), were uniformly applied to each lysimeter on the 15th April 1989, the 22nd October 1989 and the 13th October 1990 respectively. Nitrogen fertilizer was Nitram (NH_4NO_3, 34.5% N).

Experimental details are given in Tables 5.2-1 and 5.2-2.

Table 5.2-1. Experimental details: barley or wheat in the lysimeter experiment from April 1989 to October 1991 (cv = cultivar, lys = lysimeter).

Code	N fertilizer level for barley	1	2	3	4
LEX89	Total (nitram g/lys)	0	1.27	2.54	3.81
	Equivalent to (kg N/ha)	0	60	120	180
	cv: RAGATTA (barley). Sowing depth: 25 - 35 mm. Harvesting date: 29/7/89.	Sowing date: 15th April 1989. Plants/lys: 28. Growing period: 105 days.			
Code	**N fertilizer level for wheat**	**1**	**2**	**3**	**4**
LEX90	Seedbed (nitram g/lys)	0	0.32	0.64	0.95
	GS2 - 3 (nitram g/lys)	0	0.70	1.40	2.10
	GS5 - 6 (nitram g/lys)	0	0.70	1.40	2.10
	GS8 - 9 (nitram g/lys)	0	0.40	0.80	1.20
	Total (nitram g/lys)	0	2.12	4.24	6.35
	Equivalent to (kg N/ha)	0	100	200	300
	cv: AVALON (wheat). Sowing depth: 25 - 35 mm. Harvesting date:23/7/90.	Sowing date: 22nd Oct 1989. Plants/lys: 25. Growing period: 274 days.			
Code	**N fertilizer for wheat**	**1**	**2**	**3**	**4**
LEX91	Seedbed (nitram g/lys)	0	0.32	0.63	0.95
	GS2 - 3 (nitram g/lys)	0	0.95	1.91	2.86
	GS5 - 6 (nitram g/lys)	0	1.50	3.00	4.50
	GS8 - 9 (nitram g/lys)	0	0.40	0.80	1.20
	Total (nitram g/lys)	0	3.17	6.34	9.51
	Equivalent to (kg N/ha)	0	150	300	450
	cv: AVALON (wheat). Sowing depth: 25 - 35 mm. Harvesting date: 25/7/91.	Sowing date: 13th Oct 1990. Plants/lys: 25. Growing period: 285 days.			

Table 5.2-2. Experimental details: nitram application on ryegrass/clover mixtures in the lysimeter experiment from April 1989 to October 1991 (lys = lysimeter).

Code	N fertilizer level	1	2	3	4	5
LEX89	Seedbed (nitram g/lys)	0	0.45	0.90	1.35	1.80
	15/5/1989(nitram g/lys)	0	0.55	1.10	1.65	2.20
	21/8/1989(nitram g/lys)	0	1.50	3.00	4.50	6.00
	16/10/1989(nitram g/lys)	0	0.67	1.35	2.02	2.70
	Subtotal (nitram g/lys)	0	3.17	6.35	9.52	12.70
	Equivalent to (kg N/ha)	0	150	300	450	600
Code	22/10/1989 (nitram g/lys)	0	0.47	0.95	1.42	1.90
	20/3/1990 (nitram g/lys)	0	0.20	0.40	0.60	0.80
LEX90	8/4/1990 (nitram g/lys)	0	0.26	0.52	0.78	1.04
	13/6/1990 (nitram g/lys)	0	0.30	0.60	0.90	1.20
	23/8/1990 (nitram g/lys)	0	0.60	1.20	1.80	2.40
	Subtotal (nitram g/lys)	0	1.83	3.67	5.50	7.34
	Equivalent to (kg N/ha)	0	86	173	260	346
Code	22/10/1990 (nitram g/lys)	0	0.48	0.96	1.44	1.92
	9/3/1991 (nitram g/lys)	0	0.16	0.32	0.47	0.63
LEX91	2/5/1991 (nitram g/lys)	0	0.60	1.20	1.80	2.40
	20/6/1991 (nitram g/lys)	0	0.80	1.60	2.40	3.20
	11/7/1991 (nitram g/lys)	0	0.80	1.60	2.40	3.20
	29/8/1991 (nitram g/lys)	0	0.34	0.67	1.01	1.35
	Subtotal (nitram g/lys)	0	3.17	6.35	9.52	12.70
	Equivalent to (kg N/ha)	0	150	300	450	600

Varieties of the mixture	Seed rate	sowing date
Antrim (perennial ryegrass)	0.212 g/lys	15th April 1989
RVP (Italian ryegrass)	0.212 g/lys	15th April 1989
Grasslands Huia (white clover)	0.177 g/lys	15th April 1989

Code	1st cut	2nd cut	3rd cut	4th cut	5th cut
LEX89	21/7/89	16/10/89			
LEX90	13/6/90	23/8/90	22/10/90		
LEX91	25/4/91	17/6/91	11/7/91	29/8/91	13/10/91

At harvest of barley and wheat, the total air-dried biomass and seed of all plants from each lysimeter were measured, and then half of each of these materials were dried at 100^0 C for 18 hours for estimation of dry matter, the remainder being dried at 65^0 C for nitrogen assessment. For the ryegrass/clover mixture, total fresh above-ground biomass of each lysimeter was measured, and material split in half for dry matter estimation and nitrogen assessment accordingly.

Weeds arising in the lysimeters were carefully pulled out manually.

Soil samples were taken from the top 0 - 15 cm of the profile of each lysimeter at the start and end of the experiment for measurement of total and extractable nitrogen. Analytical methods are described in Chapter 2.

Leachate was checked at 20-day intervals or after rainfall on a 24-hour basis, and sampled if present. The samples (20 ml from each lysimeter) were acidified with one drop of concentrated (18 M) sulphuric acid and stored just above zero prior to analysis.

Data on the rainfall of the region was obtained from the Ness Botanic Gardens meteorological station. Rainfall receipts were then transformed to a lysimeter surface area basis (1 mm rainfall = 73 ml/lysimeter).

Since an unbalanced factorial experiment design was employed a general linear model procedure (SAS 1990) was used for analysis of variance. In the method employed, Type III hypotheses were used to investigate treatment effects. These do not depend on the number of observations for each combination of the factors, but only on which combinations are observed although some authorities (Milliken and Johnson 1984) do not place much reliance on Type III hypotheses. For analysis of variance of yield components in this experimental design, the total number of observations was 27 and the total degrees of freedom therefore was 26. The total number of treatments for yield was 9 and hence model degrees of freedom were 8 (Table 5.2-3).

Table 5.2-3. Factorial combinations with levels of each factor for the lysimeter experiment from 15 April 1989 to 13 October 1991. NFL[1] = nitrogen fertilizer level, Tr = treatment, Re = replicate, G/C M = ryegrass/clover mixture.

Factors	Crop			
	G/C M	Cereal[2]	Control[3]	Observations
NFL 1	Tr 1*3Re	Tr 2*3 Re	Tr 10*3 Re	9
NFL 2	Tr 3*3 Re	Tr 4*3 Re	missing	6
NFL 3	Tr 5*3 Re	Tr 6*3 Re	missing	6
NFL 4	Tr 7*3 Re	Tr 8*3 Re	missing	6
NFL 5	Tr9*3 Re	missing	missing	6
Total	15	12	3	30

1. Nitrogen fertilizer level are given in Tables 5.2-1 and 5.2-2.
2. Barley for the first year, followed by wheat in the 2nd and 3rd years.
3. Control occurs only for leachate and nitrate concentration of the leachate.

The number of crops examined was two in each cropping season which gives one degree of freedom for this source of variation. The total number of fertilizer levels was 5, giving four degrees of freedom for this source. Therefore the degrees of freedom for the crop fertilizer interaction were 3, i.e. 8 - 1 - 4 = 3.

For analysis of variance of leachate, the degrees of freedom follow a similar pattern except that crop degrees of freedom are increased by one and the error degrees of freedom to 20 since the control (non-plant and non-fertilizer treatment) was included. The method of calculation of least significant differences is given in Appendix B.

During analysis, data were inspected for heterogeneity of error variance, but there was no requirement for data transformation.

Equation (10), discussed in Chapter 1, again was fitted to the data to enable comparisons of yield and nitrogen relationships.

To assess the long-term effects of the crops and N fertilizer application on the nitrate concentration of the leachate a weighted mean was calculated for each lysimeter using the following formula :

$$WMNC = \frac{\sum_{i=1}^{n} (NC_i * LV_i)}{\sum_{i=1}^{n} LV_i}$$

WMNC (ppm) stands for weighted mean of nitrate concentration; NC_i is the nitrate concentration (ppm) of a leachate collected at date i; LV_i is the volume (ml) of the leachate collected at date i; n is the total number of the leachates collected for the particular lysimeter.

Total nitrate loss in the leachate over the period 15th April 1989 to 13th October 1991 was calculated using the formula :

$$TNL = (\sum_{i=1}^{n} (NC_i * LV_i)) * 10^{-6}$$

TNL (g N /lysimeter) stands for total nitrate loss in leachate; NC_i, LV_i, and n are defined as above.

5.3 Results

5.3.1 Results of cropping season LEX89

(1) Yields of barley and ryegrass/clover mixture

The biomass and seed yields of spring sown barley and the ryegrass/clover mixture differed very significantly ($P < 0.01$) from each other at harvest (Table 5.3.1-1). There was a highly significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass and economic yields of the two crops overall, and the response to nitrogen fertilizer level was significantly different ($P < 0.01$) between the two crops (interactions) both for biomass and economic yield.

Table 5.3.1-1. Analysis of variance of biomass and economic yields of barley and ryegrass/clover mixture (season LEX89).

Yield	Source	DF	Sum of squares	F	P_{HO}
Biomass	Crop	1	146.7	43.3	0.0001
	Fertilizer	4	753.9	55.7	0.0001
	Crop*fertilizer	3	326.0	32.1	0.0001
	Error	18	60.9		
	Total	26	1439.1		
Grain or Herbage	Crop	1	4292.2	2213.0	0.0001
	Fertilizer	4	662.7	85.4	0.0001
	Crop*fertilizer	3	399.8	68.7	0.0001
	Error	18	34.9		
	Total	26	6508.7		

Comparison of means for biomass and economic yields, pooling over fertilizer application, indicates that the biomass of the ryegrass/clover mixture was 19% higher than that of barley and 3.16 fold higher than the seed yield (13.2 ± 0.3 g/lys) of barley (Fig 5.3.1-1).

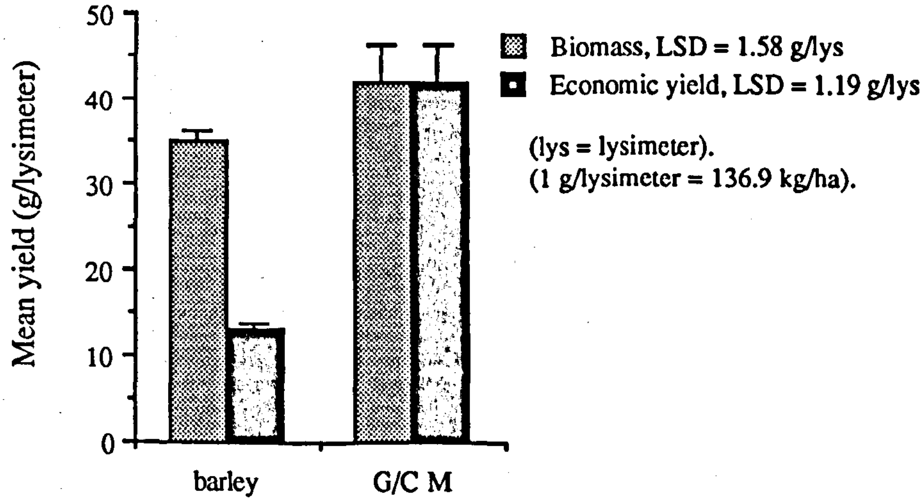

Fig 5.3.1-1. Comparison of crop yields, using pooled data over nitrogen fertilizer application (cropping season LEX89) from April 1989 to October 1989. Confidence limits are standard errors of the mean. G/C M = ryegrass/clover mixture.

(2) Yield response to fertilizer

The biomass and economic yield of barley and the ryegrass/clover mixture showed a positive response to nitrogen fertilizer. Parameter estimates, and their standard errors, of equation (10) are given in Table 5.3.1-2.

Table 5.3.1-2. Parameters and their standard errors after model fitting for each crop (season LEX89). SE = Standard error, G/C M = ryegrass/clover mixture, B = biomass in g/lysimeter, E = economic yield in g/lysimeter.

Crops	b_0	b_0SE	b_1	b_1SE	b_2	b_2SE	b_3	b_3SE	R^2
Barley B	33.11	1.2	1.74	1.5	0	0	6.8e-3	1.1e-2	0.9974
Barley E	12.58	0.6	0.82	0.8	0	0	7.3e-3	1.6e-2	0.9951
G/C M	26.89	0.9	3.65	2.0	-1.3e-2	4.7e-2	4.2e-3	8.3e-4	0.9990

Although the mean yields of barley at levels of N fertilizer application showed that there was a positive response to nitrogen fertilizer (Fig 5.3.1-2), means did not statistically differ from one another.

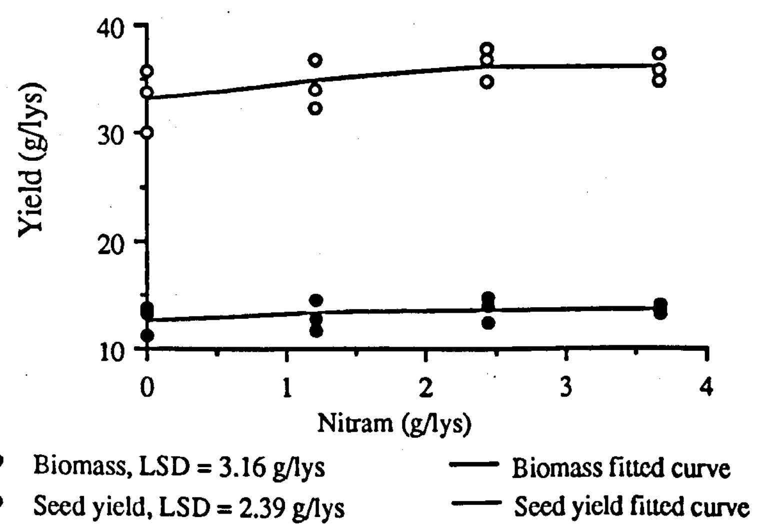

Fig 5.3.1-2. The yield of barley in response to nitrogen fertilizer (cropping season LEX89) from April 1989 to October 1989. (lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha).

Fitted curves of biomass (g/lysimeter) and seed yield (g/lysimeter) are :

$$\text{Biomass} = \frac{33.11 + 1.74N}{1 + 0.0068N^2}$$

and

$$\text{Seed yield} = \frac{12.58 + 0.82N}{1 + 0.0073N^2}$$

where N is nitrogen fertilizer in g nitram/lysimeter.

The economic response of barley grain (13.2 g/lys) was obtained at the nitrogen fertilizer level of 1 g nitram/lys (equivalent to 47.2 kg N/ha).

The ryegrass/clover mixture, however, showed a significant response to nitrogen fertilizer (Fig 5.3.1-3).

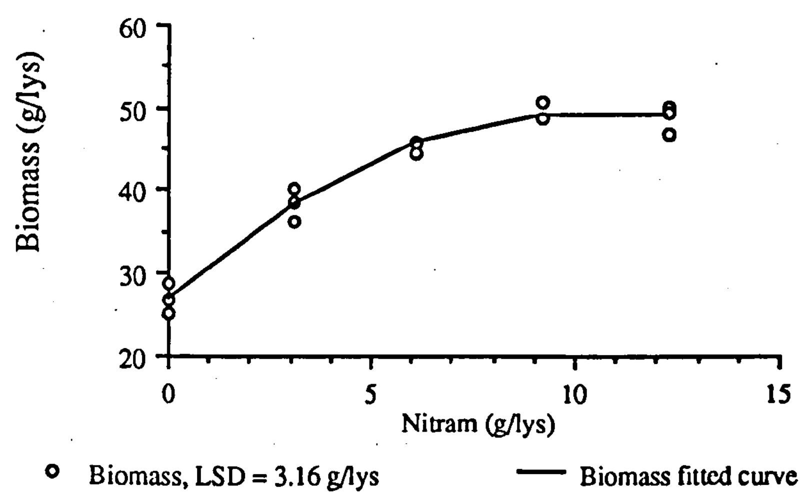

Fig 5.3.1-3. The biomass of ryegrass/clover mixture in response to nitrogen fertilizer (cropping season LEX89) from April 1989 to October 1989. (lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha).

The response of biomass (g/lysimeter) to nitrogen is described by the equation

$$\text{Biomass} = \frac{26.89 + 3.65N}{1 - 0.013N + 0.0042N^2}$$

where N is nitrogen fertilizer in g nitram/lysimeter.

The economic response (48.2 g/lys) occurred at a nitrogen level of 9.0 g nitram/lys (equivalent to 378 kg N/ha).

(3) Effect of crops on the volume of leachate

In this season, rainfall provided the only means for lysimeter leachate since no artificial watering occurred. For a given soil and climate, the volume of leachate depends on the rate of water loss by means of transpiration from vegetation and the evaporation from the surface of the soil, both of which will depend on crop type. The results of this season suggested that crops have a very significant ($p < 0.01$) effect on reducing leachate since there was no leachate from the lysimeters under barley for the entire growth season from April 1989 to October 1989, but a significant volume of leachate from lysimeters with no plants (control) in the last three months of the season (Fig 5.3.1-4). A small volume of leachate from 4 out of the 15 lysimeters under the ryegrass/clover mixture was also observed in September 1989.

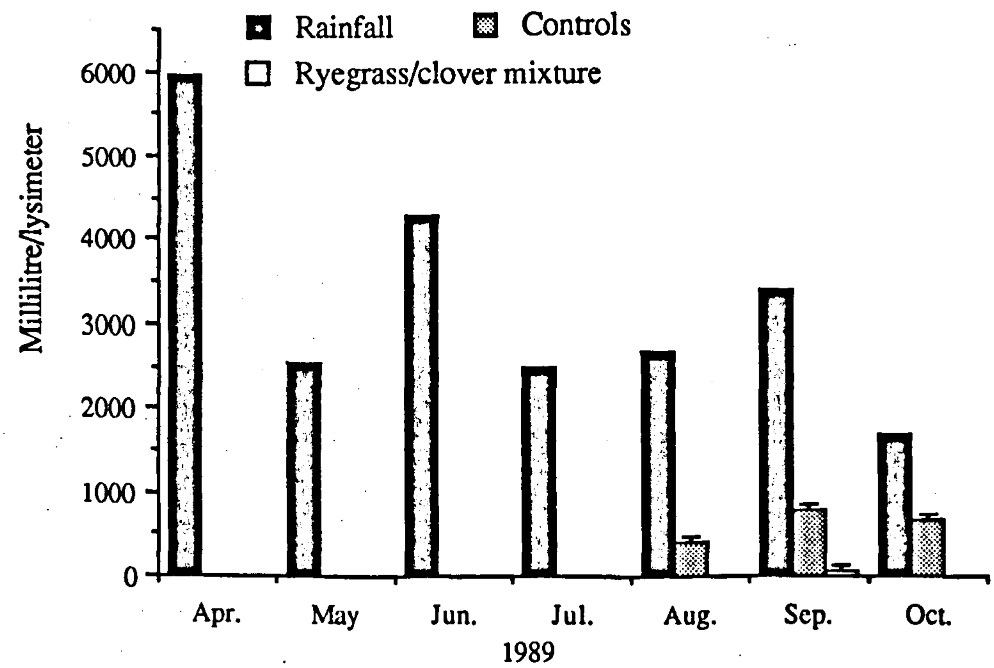

Fig 5.3.1-4. Distribution of rainfall and leachate per lysimeter (0.073 square meter), pooled data over fertilizer application (cropping season LEX89) from April 1989 to October 1989). Confidence limits are standard errors of the mean.

Statistical analysis showed that the leachate volume of the controls differed very significantly ($p < 0.01$) from those of barley and the ryegrass/clover mixture.

(4) Nitrate concentration of the leachate

The nitrate assessment for the only leachates collected in this season (LEX89) indicated that the nitrate concentration of the leachates, (39.6 to 97.7 mg NO_3-N/l), were much higher than the World Health Organization criteria for drinking water, 11.3 mg NO_3-N/l for the upper limit of the safe level and 22.6 mg NO_3-N/l for the upper limit of the acceptable level (Fig 5.3.1-5).

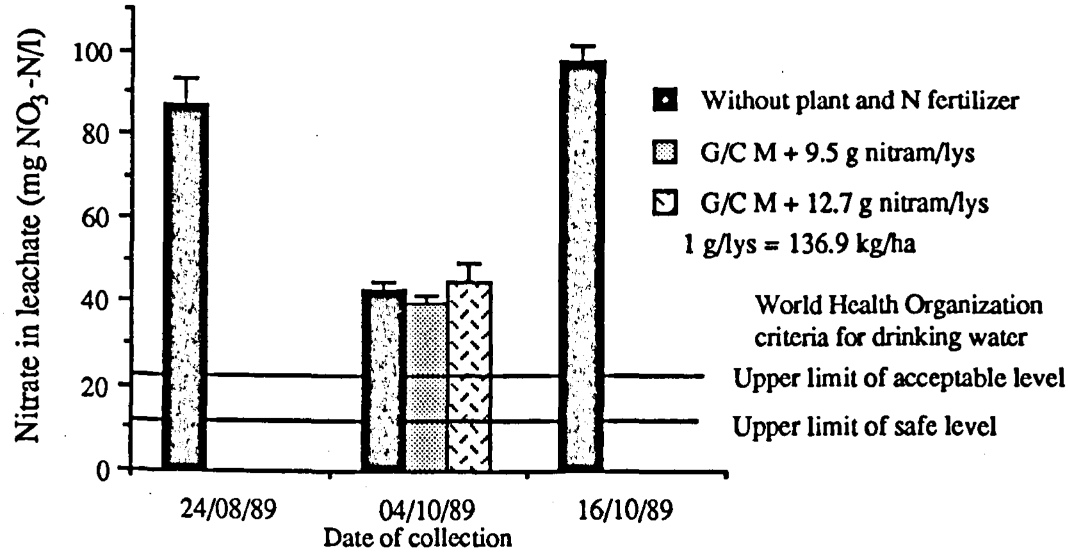

Fig 5.3.1-5. Comparison of effects of crop and N fertilizer application on the concentration of nitrate in leachate (cropping season LEX89). Confidence limits are standard errors of the mean. (G/C M = ryegrass/clover miture, lys = lysimeter).

Because no leachate was collected from lysimeters under barley and from 11 lysimeters out of the 15 under the ryegrass/clover mixture, the effects of crops and N fertilizer application on the nitrate concentration could not be clearly assessed. The results showed, however, that mineralized soil nitrogen (NO_3-N), if not taken up by plants, would be leached out of the root zone when leaching occurred.

5.3.2 Results of cropping season LEX90

(1) Yields of wheat and ryegrass/clover mixture

In the 1989 - 90 cropping season, the biomass and economic yield of wheat differed very significantly ($P < 0.01$) from that of the ryegrass/clover mixture (Table 5.3.2-1). There was a highly significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass and economic yields of the crops in general. Nitrogen fertilizer level also had significant differential effects on the biomass and economic yields of the two crops ($P < 0.01$).

Table 5.3.2-1. Analysis of variance of biomass and economic yields of autumn sown wheat and ryegrass/clover mixture (season LEX90).

Yield	Source	DF	Sum of squares	F	P_{HO}
Biomass	Crop	2	8658.0	1280.6	0.0001
	Fertilizer	4	5166.3	382.1	0.0001
	Crop*Fertilizer	3	652.9	64.4	0.0001
	Error	20	67.6		
	Total	29	22272.6		
Grain or Herbage	Crop	2	13015.7	2108.5	0.0001
	Fertilizer	4	4525.7	366.6	0.0001
	Crop*fertilizer	3	1071.2	115.7	0.0001
	Error	20	61.7		
	Total	29	27151.3		

Pooling over nitrogen fertilizer application, mean yields of the biomass of the ryegrass/clover mixture was 3.9 times higher than that of wheat, its economic yield being 10.9 times greater than that of wheat (Fig 5.3.2-1).

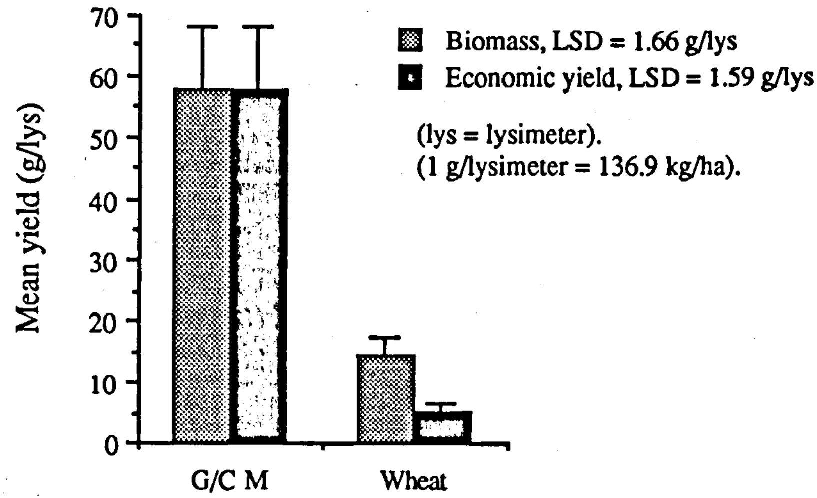

Fig 5.3.2-1. Comparison of crop yields, using pooled data over nitrogen fertilizer application (cropping season LEX90) from October 1989 to October 1990. Confidence limits are standard errors of the mean. G/C M = ryegrass/clover mixture.

(2) Crop yield response to nitrogen fertilizer

The goodness of fit of equation (10) was high ($R^2 > 0.99$) for all data sets and parameter values are given in Table 5.3.2-2.

Table 5.3.2-2. Parameters and their standard errors after model fitting for each crop (season LEX90). SE = Standard error, G/C M = ryegrass/clover mixture, B = biomass in g/lysimeter, E = economic yield in g/lysimeter.

Crops	b_0	b_0SE	b_1	b_1SE	b_2	b_2SE	b_3	b_3SE	R^2
Wheat B	8.22	0.6	2.35	0.4	-4.0e-4	0	3.0e-3	3.0e-3	0.9964
Wheat E	3.02	0.2	0.86	0.1	-4.0e-4	0	3.3e-3	2.9e-3	0.9966
G/C M	31.29	1.5	3.85	4.7	-7.7e-2	1.0e-1	4.6e-3	6.8e-3	0.9986

Comparison of parameter values suggest that both biomass of wheat (Fig 5.3.2-2) and the ryegrass/clover mixture (Fig 5.3.2-3) responded significantly to nitrogen fertilizer application, but the seed yields of wheat were statistically similar at all levels of nitrogen fertilizer application.

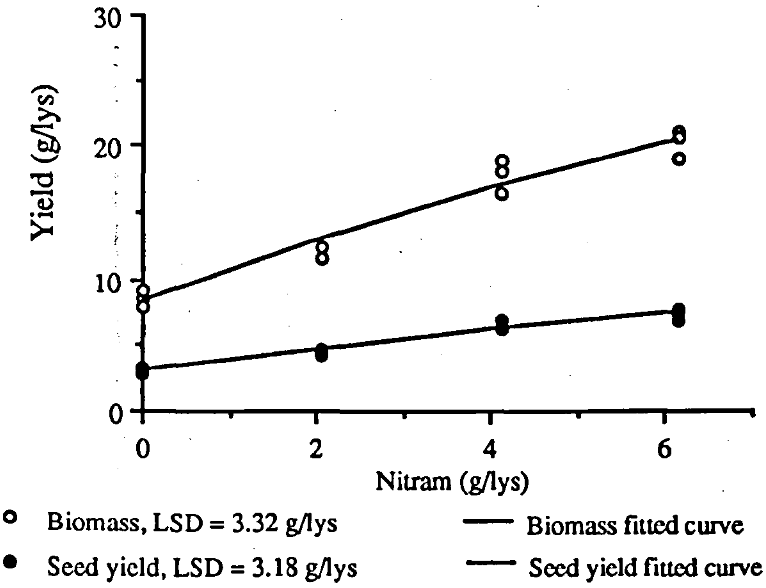

Fig 5.3.2-2 The yield of wheat in response to nitrogen fertilizer (cropping season LEX90) from October 1989 to October 1990. (lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha).

Yield response of wheat to fertilizer are described by the following equations

$$\text{Biomass} = \frac{8.22 + 2.35N}{1 - 0.0004N + 0.003N^2}$$

and

$$\text{Seed yield} = \frac{3.02 + 0.86N}{1 - 0.0004N + 0.0033N^2}$$

where N is nitrogen fertilizer in g nitram/lysimeter.

An economic response of 5 g/lys for wheat grain yield was calculated to occur at a N fertilizer level of 3 g nitram/lys.

In contrast to the other responses reported the yield relationship for the ryegrass/clover mixture was predominantly linear (Fig 4.3.2-3) and could be described by the equation

$$\text{Biomass} = \frac{31.29 + 3.85N}{1 - 0.077N + 0.0046N^2}$$

where Biomass is in g/lysimeter and N is nitrogen fertilizer in g nitram/lysimeter.

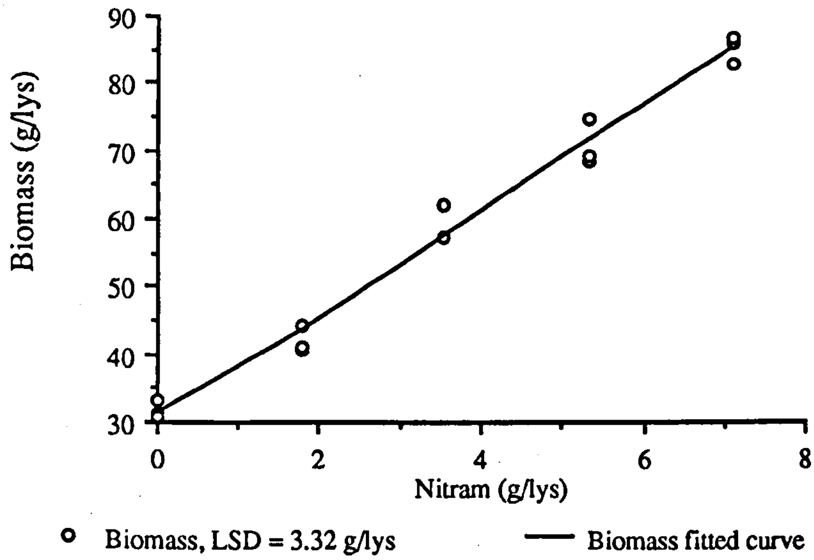

Fig 5.3.2-3. The biomass of ryegrass/clover mixture in response to nitrogen fertilizer (cropping season LEX90) from October 1989 to October 1990. (lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha).

Maximum yield, 87 g/lys, was recorded at the highest nitrogen application level of 7.34 g nitram/lysimeter, which is equivalent to 346 kg N/ha.

(3) Effect of crops on the volume of leachate

During the period of crop growth in 1989 - 90, leachate was observed and collected from November 1989 to late February 1990 and during October 1990. Statistical analysis of the total volume of leachate collected over the entire growing season (22nd October 1989 to 13th October 1990) indicated that both crops and fertilizer level significantly ($p < 0.01$) affected the volume of leachate (Table 5.3.2-3).

Table 5.3.2-3. Analysis of variance of leachate volume collected from 22nd October 1989 to 13th 1990 (season LEX90).

Time	Source	DF	Sum of squares	F	P_{HO}
Whole season	Crop	2	60827979	29.3	0.0001
	Fertilizer	4	117498224	28.3	0.0001
	C*F	3	10780796	3.5	0.0001
	Error	20	20748275		
	Total	29	315090565		

Monitoring of rainfall receipts from 22nd October 1989 to 13th October 1990 indicated that in November and December 1989 and in January and February 1990 high volumes of rainfall were received, and subsequent three months (March to May in 1990) of low rainfall occurred. Rainfall was intermediate from June to October 1990 except for low volumes in July 1990. The monthly pattern of leachate volume across treatments including controls followed that of rainfall. In all months except December 1989, the least leachate was collected from the lysimeters under the ryegrass/clover with more leachate being collected under wheat. The control treatment gave the most leachate throughout, with the exception of volumes recorded in December 1989 (Fig 5.3.2-4).

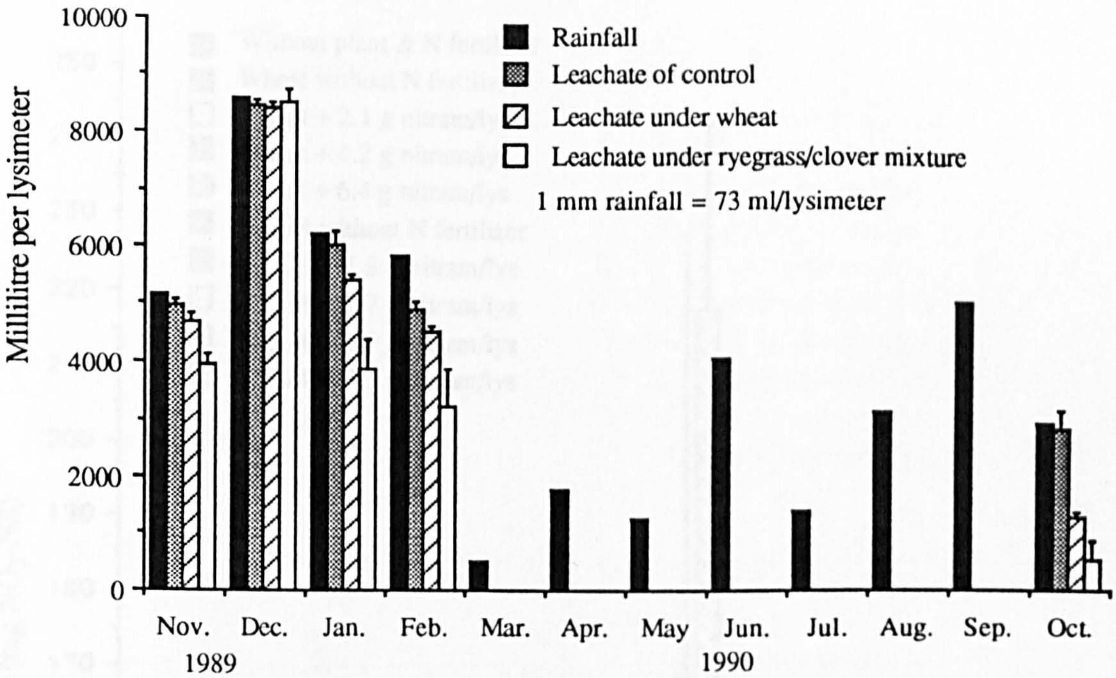

Fig 5.3.2-4. Distribution of rainfall and leachate per lysimeter (0.073 square meter), pooled data over fertilizer application (cropping season LEX90) from October 1989 to October 1990. Confidence limits are standard errors of the mean.

(4) Nitrate concentration of the leachate

Results suggested that the nitrate concentration of the leachates was mainly dominated by N fertilizer application (Fig 5.3.2-5A and Fig 5.3.2-5B). The higher the N fertilizer application, the higher the nitrate concentration. Seasonal variation was also observed. The nitrate concentration was higher in the leachates collected in November 1989 and on 4th January 1990 than in those collected in middle January, early February and March in 1990, when compared at each N fertilizer level respectively.

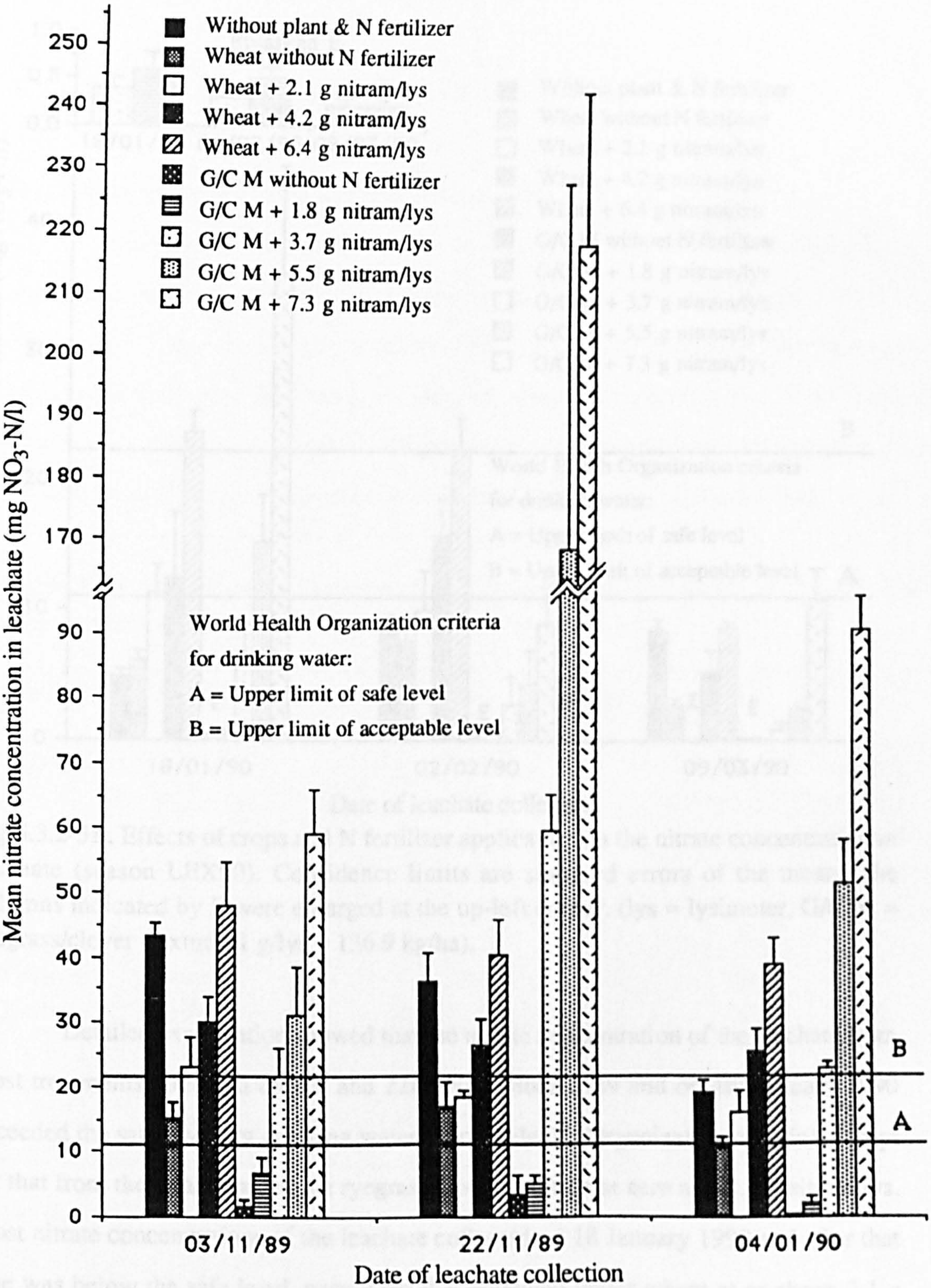

Fig 5.3.2-5A. Effects of crops and N fertilizer application on the nitrate concentration in leachate (season LEX90). Confidence limits are the standard errors of the mean. (G/C M = ryegrass/clover mixture, 1 g/lys = 136.9 kg/ha, lys = lysimeter).

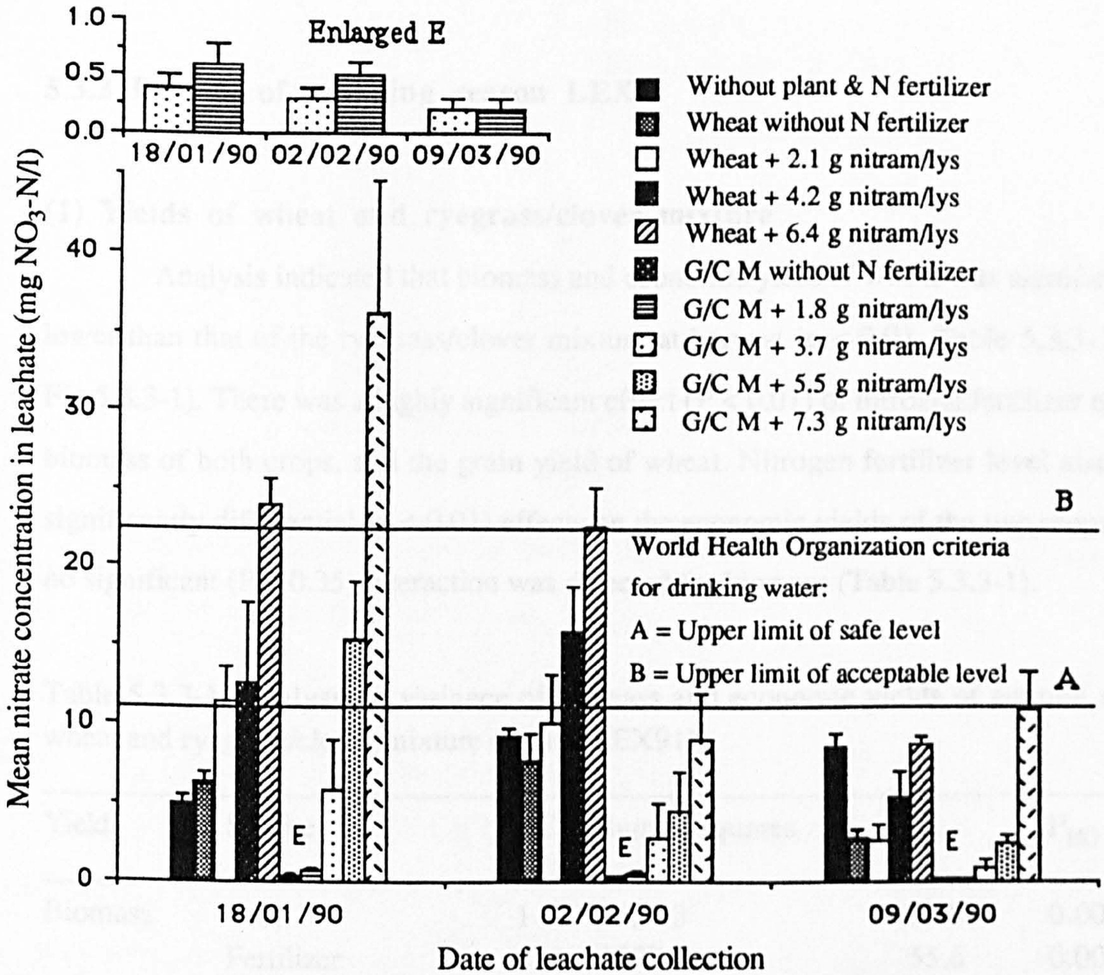

Fig 5.3.2-5B. Effects of crops and N fertilizer application on the nitrate concentration in leachate (season LEX90). Confidence limits are standard errors of the mean. The columns indicated by E were enlarged at the up-left corner. (lys = lysimeter, G/C M = ryegrass/clover mixture, 1 g/lys = 136.9 kg/ha).

Detailed examination showed that the nitrate concentration of the leachate from most treatments collected on 3rd and 22nd November 1989 and on 4th January 1990 exceeded the safe level for drinking water (World Health Organization criteria), except for that from the treatments of the ryegrass/clover mixture at zero and 2.1 g nitram/lys. Most nitrate concentrations of the leachate collected on 18 January 1990 and after that date was below the safe level, except for that collected under wheat at or above 2.1 g nitram/lys treatments and under ryegrass/clover mixture at 5.5 and 7.3 g nitram/lys. Two extremely high concentrations (167.9 ± 59.2 and 217.1 ± 24.8 mg NO_3-N/l) were detected in the leachates collected on 22 November 1989 from the lysimeters under the ryegrass/clover receiving 5.5 and 7.3 g nitram/lysimeter.

5.3.3 Results of cropping season LEX91

(1) Yields of wheat and ryegrass/clover mixture

Analysis indicated that biomass and economic yield of wheat was significantly lower than that of the ryegrass/clover mixture at harvest ($p < 0.01$, Table 5.3.3-1 and Fig 5.3.3-1). There was a highly significant effect ($P < 0.01$) of nitrogen fertilizer on the biomass of both crops, and the grain yield of wheat. Nitrogen fertilizer level also had significantly differential ($p < 0.01$) effects on the economic yields of the two crops, but no significant ($P > 0.35$) interaction was detected for biomass (Table 5.3.3-1).

Table 5.3.3-1. Analysis of variance of biomass and economic yields of autumn sown wheat and ryegrass/clover mixture (season LEX91).

Yield	Source	DF	Sum of squares	F	P_{HO}
Biomass	Crop	1	1957.3	160.9	0.0001
	Fertilizer	4	2707.2	55.6	0.0001
	Crop*fertilizer	3	42.9	1.2	0.3472
	Error	18	219.0		
	Total	26	5666.8		
Grain or Herbage	Crop	1	9878.2	1946.1	0.0001
	Fertilizer	4	1428.2	70.3	0.0001
	Crop*fertilizer	3	228.0	14.5	0.0001
	Error	18	91.4		
	Total	26	13858.4		

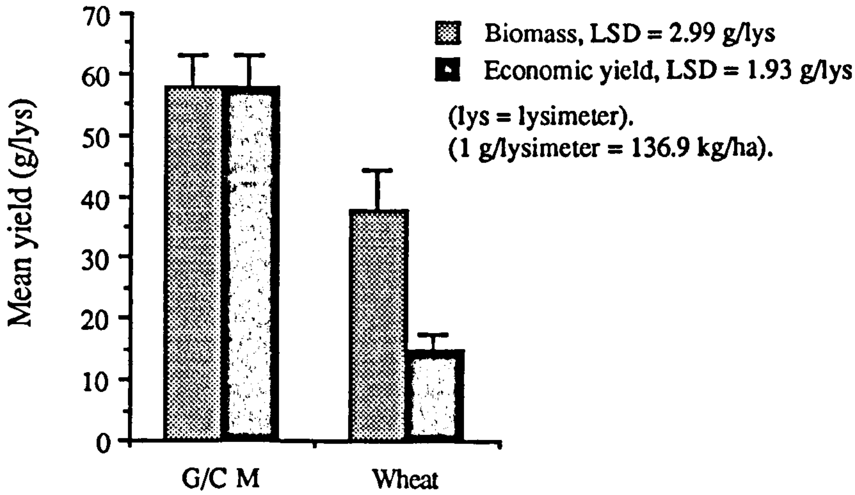

Fig 5.3.3-1. Comparison of crop yields, using pooled data over nitrogen fertilizer application (cropping season LEX91) from October 1990 to October 1991. Confidence limits are standard errors of the mean.
G/C M = ryegrass/clover mixture.

(2) Crop yield response to nitrogen fertilizer

Figs 5.3.3-2 and 5.3.3-3 show the yield responses of wheat and herbage mixture to nitrogen respectively. For both crops in this season, yield increased with added nitrogen application and Table 5.3.3-2 gives parameter values for equation (10).

Table 5.3.3-2. Parameters and their standard errors after fitting the equation (10) for each crop (season LEX91). SE = Standard error, G/C M = ryegrass/clover mixture, B = biomass in g/lysimeter, E = economic yield in g/lysimeter.

Crops	b_0	b_0SE	b_1	b_1SE	b_2	b_2SE	b_3	b_3SE	R^2
Wheat B	20.15	2.3	7.3	1.4	0	0	1.1e-2	3.5e-3	0.9922
Wheat E	8.25	0.8	2.12	2.0	-4.0e-2	0.12	1.1e-2	3.3e-3	0.9949
G/C M	40.32	1.5	3.66	3.7	-2.1e-2	6.1e-2	3.7e-3	9.4e-4	0.9985

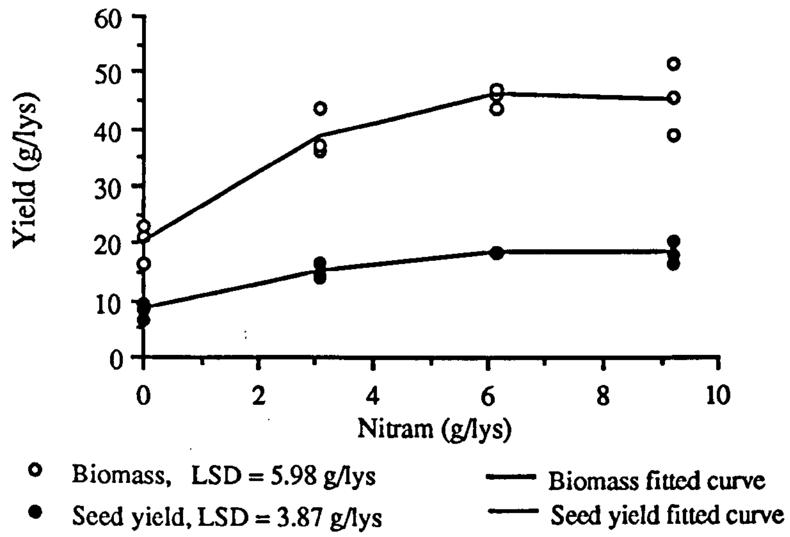

Fig 5.3.3-2. The yield of wheat in response to nitrogen fertilizer (cropping season LEX91) from October 1990 to October 1991. (lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha)

The fitted curves of the biomass (g/lysimeter) and seed yield (g/lysimeter) of wheat (Fig 5.3.3-2) are described by the equations

$$\text{Biomass} = \frac{20.15 + 7.3N}{1 + 0.011N^2}$$

and

$$\text{Seed yield} = \frac{8.25 + 2.12N}{1 - 0.0004N + 0.011N^2}$$

where N is nitrogen fertilizer in g nitram/lysimeter.

The analysis suggests that there is an optimal level of N for both maximal biomass and grain. The economic grain yield response (14.2 g/lys) was estimated to be 4 g nitram/lysimeter (equivalent to 189 kg N/ha).

Equation (10) fitted to the biomass (g/lysimeter) of the herbage mixture is

$$\text{Biomass} = \frac{40.32 + 3.66N}{1 - 0.021N + 0.0037N^2}$$

where N is nitrogen fertilizer in g nitram/lysimeter and is illustrated in Fig 5.3.3-3.

9 g nitram/lysimeter (425 kg N/ha) gave an economic response of 66.0 g/lys.

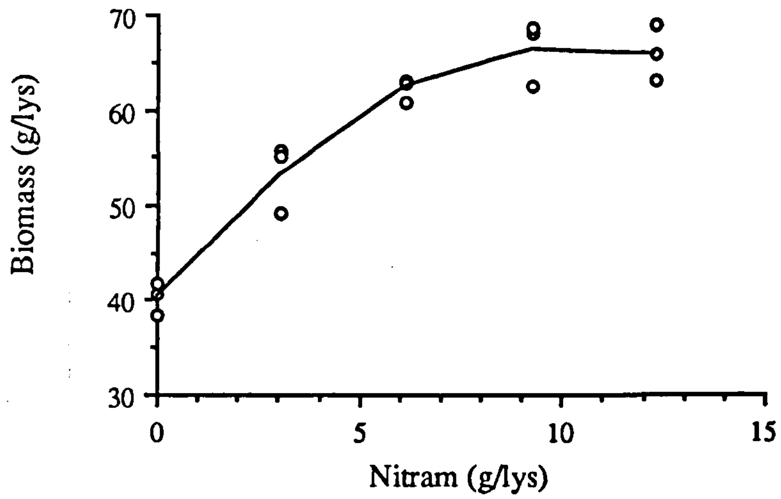

Fig 5.3.3-3. The biomass of ryegrass/clover mixture in response to nitrogen fertilizer (cropping season LEX91) from October 1990 to October 1991.
(lys = lysimeter, 1 g/lysimeter = 136.9 kg/ha).

—— Biomass fitted curve

(3) Effect of crops on the volume of leachate

From 13th October 1990 to 13th October 1991, there were two short periods of drought with 10.8 mm of rainfall from 1st to 31st in May and 15.3 mm from the first of the August to the 13th of the September in 1991. No leachate was collected in April and from July to September in 1991 and there was only a small volume of leachate collected from control treatments in May, June and October in 1991 (Fig 5.3.3-4). Most of the leachate occurred and collected from November 1990 to March 1991.

Highest rainfall occurred during November 1990 and thereafter rainfall declined from December 1990 to October 1991 with the exception of heavy precipitation in June 1991.

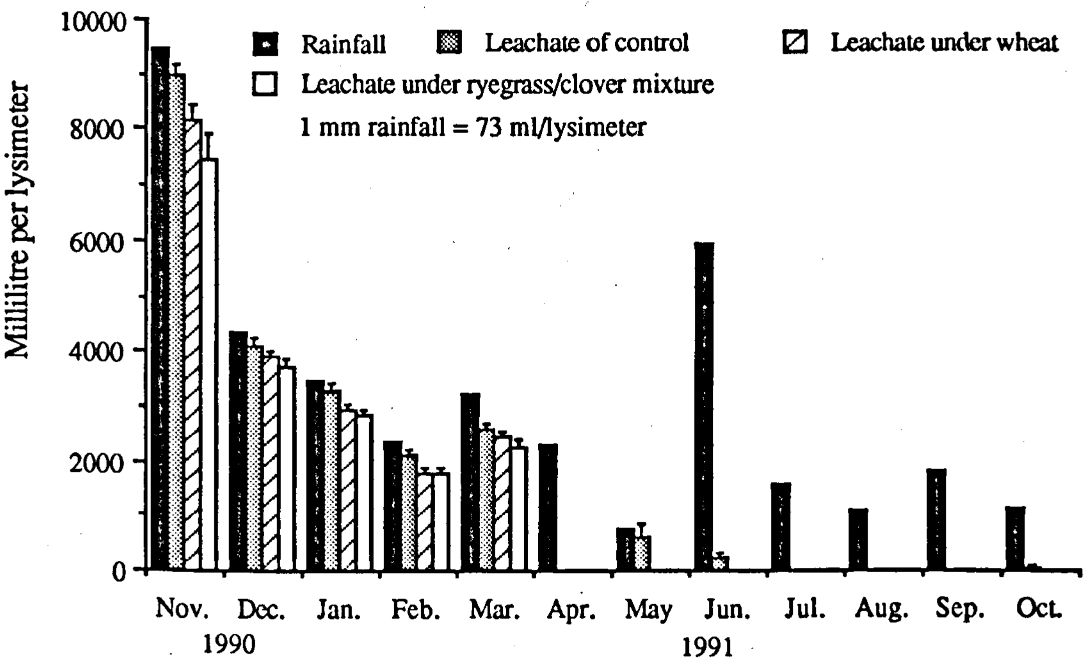

Fig 5.3.3-4. Distribution of rainfall and leachate per lysimeter, pooled data over fertilizer application (cropping season LEX91) from October 1990 to October 1991. Confidence limits are standard errors of the mean.

The monthly pattern of leachate volume amongst crops and controls was similar to that in the previous season (LEX90), with the lowest from the lysimeters under the ryegrass/clover mixture, highest from the controls and those under wheat being intermediate.

An analysis of variance of the total leachate from 13th October 1990 to 13th October 1991, suggested that crops and fertilizer level significantly ($p < 0.01$) affected the volume of leachate over the period (Table 5.3.3-3).

Table 5.3.3-3. Analysis of variance of leachate volume collected from 13th October 1990 to 13th 1991 (season LEX91). C*F = crop*fertilizer.

Time	Source	DF	Sum of squares	F	P_{HO}
Whole season	Crop	2	15086902	20.49	0.0001
	Fertilizer	4	29462329	20.01	0.0001
	C*F	3	10361161	9.38	0.0004
	Error	20	7361834		
	Total	29	89962765		

(4) Nitrate concentration of the leachate

Nitrate assessment of the leachates collected from 13th October 1990 to 13th October 1991 suggested that the effects of crops and N fertilizer application were similar to those observed in the previous year. Nitrate concentration of the leachates showed monthly variation. The effects of N fertilizer application did not directly relate to the nitrate concentration for leachates collected in March 1991 (Fig 5.3.3-5A and Fig 5.3.3-5B).

High nitrate concentration above the World Health Organization's acceptable level was observed in 5 instances for the control (Fig 5.3.3-5A & Fig 5.3.3-5B). In the leachates collected from the lysimeter under wheat, nitrate concentration commonly exceeded the safe level in October, November and December 1990 and in May 1991. There were two instances, 31 December 1990 and on 27 May 1991, of the treatment at 3.2 g nitram/lys below the safe level. For the nitrate concentration in leachate under the ryegrass/clover mixture, however, the safe level was exceeded only at a N fertilizer rate above 9.5 g nitram/lys in October and December in 1990 and above 3.2 g nitram/lys in May 1991.

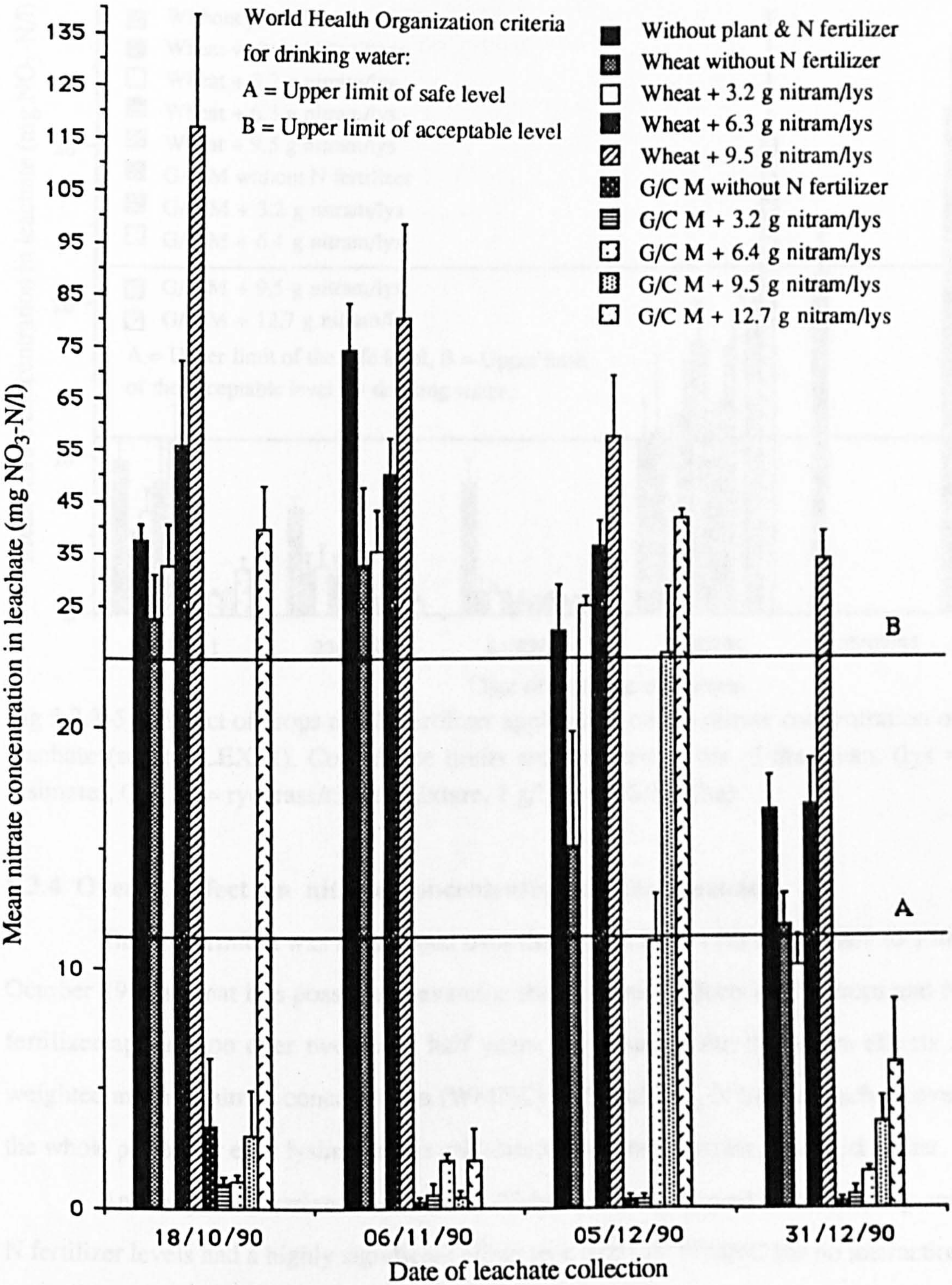

Fig 5.3.3-5A. Effect of crops and N fertilizer application on the nitrate concentration of leachate (season LEX91). Confidence limits are standard errors of the mean. (lys = lysimeter, G/C M = ryegrass/clover mixture, 1 g/lys = 36.9 kg/ha).

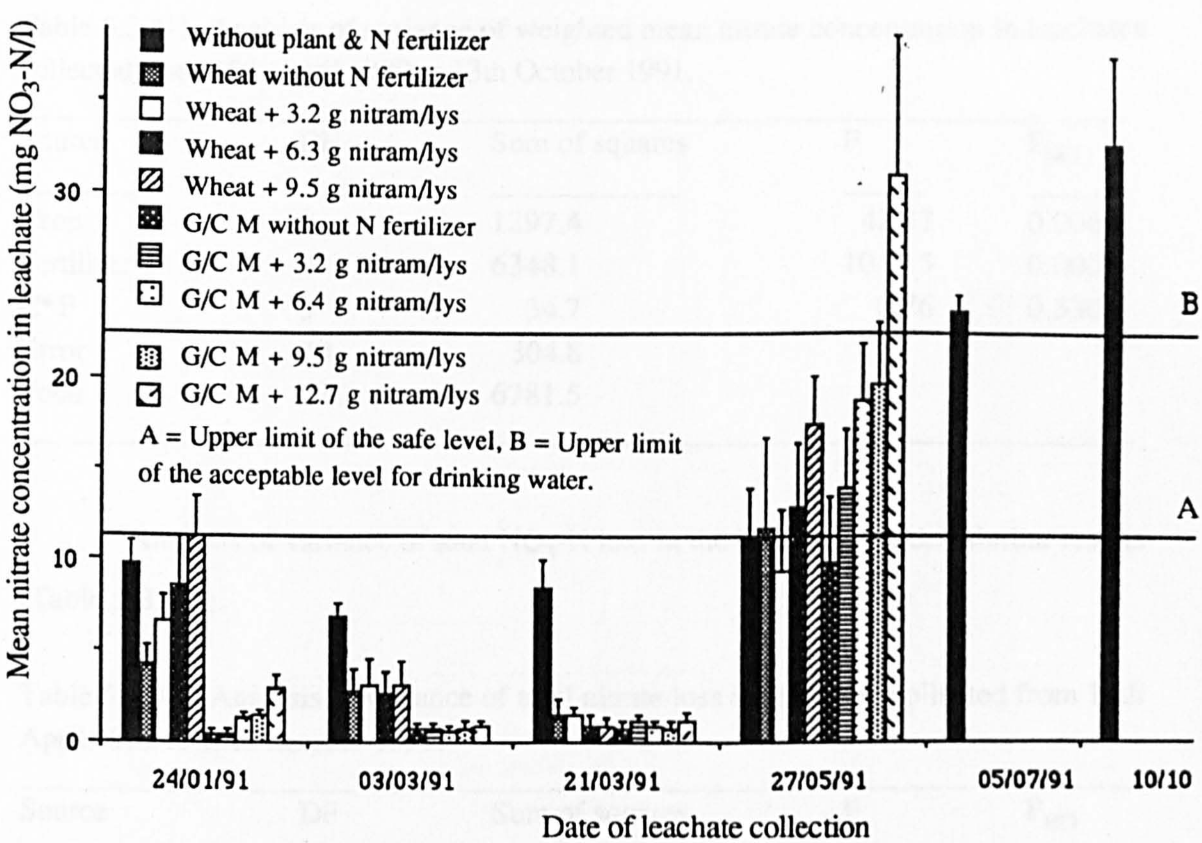

Fig 5.3.3-5B. Effect of crops and N fertilizer application on the nitrate concentration of leachate (season LEX91). Confidence limits are standard errors of the mean. (lys = lysimeter, G/C M = ryegrass/clover mixture, 1 g/lys = 136.9 kg/ha).

5.3.4 Overall effect on nitrate concentration of the leachate

This experiment was maintained over the period from 15th April 1989 to 13th October 1991 so that it is possible to examine the long term effects of the crops and N fertilizer application over two and a half years. To describe the long-term effects a weighted mean of nitrate concentration (WMNC) and total NO_3-N loss in leachate over the whole period for each lysimeter was calculated using the formulas described earlier.

An analysis of variance of WMNC (Table 5.3.4-1) showed that both crop and N fertilizer levels had a highly significant effect ($p < 0.01$) on WMNC but no interaction between crop and fertilizer levels was significant.

Table 5.3.4-1. Analysis of variance of weighted mean nitrate concentration in leachates collected from 15th April 1989 to 13th October 1991.

Source	DF	Sum of squares	F	P_{HO}
Crop	2	1297.4	42.57	0.0001
Fertilizer	4	6348.1	104.15	0.0001
C*F	3	34.7	0.76	0.5301
Error	20	304.8		
Total	29	6781.5		

Analysis of variance of total NO_3-N loss in the leachates yielded similar results (Table 5.3.4-2).

Table 5.3.4-2. Analysis of variance of total nitrate loss in leachates collected from 15th April 1989 to 13th October 1991.

Source	DF	Sum of squares	F	P_{HO}
Crop	2	3.441	63.32	0.0001
Fertilizer	4	7.368	67.79	0.0001
C*F	3	0.009	0.11	0.9539
Error	20	0.543		
Total	29	9.066		

Comparison of observed mean nitrate concentration with World Health Organization criteria for NO_3-N concentration in drinking water showed that the control treatment exceeded the upper limit of the defined acceptable level, as did ryegrass/clover mixture with a N fertilizer application over the period at or above a total of 24.54 g nitram/lys and wheat with N fertilizer application at a total of 19.67 g nitram/lys. The nitrate concentration of leachate under all wheat treatments including zero N fertilizer application exceeded the upper limit of the safe level. In the ryegrass/clover mixture however, nitrate concentration exceeded the upper limit of the safe level at or above a total fertilizer application of 16.37 g nitram/lys (Fig 5.3.4-1).

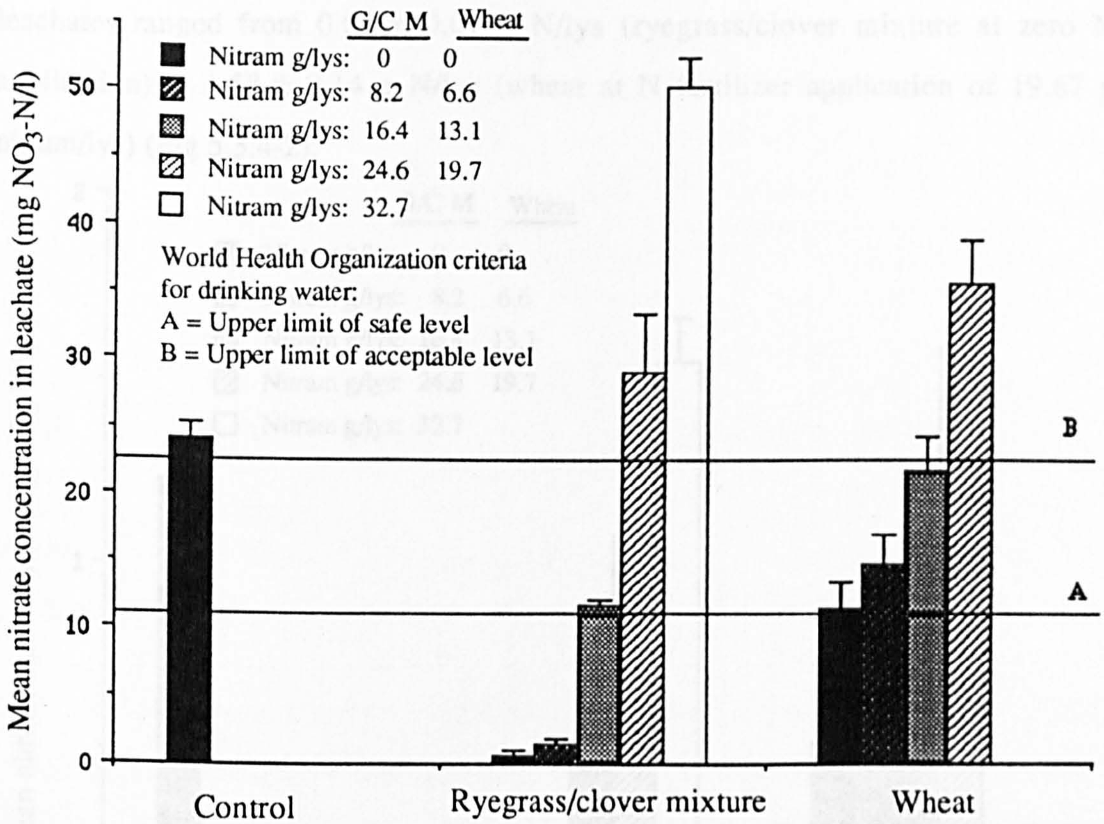

Fig 5.3.4-1. Comparison of weighted mean nitrate concentration in the leachate over the period from 15th April 1989 to 13th October 1991 between the crops and fertilizer application. Confidence limits are standard errors of the mean. N fertilizer levels refer to materials and methods in this chapter. LSD = 6.65 mg NO_3-N/l.

The relationship between nitrate concentration and N fertilizer application were illustrated by two equations:

$$Y = 14.30 - 5.29X + 2.65X^2 \text{ in wheat } (R^2 = 0.999) \text{ and}$$

$$Y = 4.52 - 7.92X + 3.44X^2 \text{ in the ryegrass/clover mixture } (R^2 = 0.998).$$

Where Y is nitrate concentration in mg NO_3-N/l and X is applied nitrogen fertilizer in kg N/ha.

The total nitrogen loss followed a similar pattern in related to treatments as was observed for weighted mean nitrate concentration. The total NO_3-N loss over the 2.5 years from the control treatment (no crop, no fertilizer addition) was 1.23 ± 0.06 g N/lys, which exceeded that from the ryegrass/clover mixture with a N fertilizer application at or below 24.54 g nitram/lys and that from wheat with N fertilizer application at or below 13.12 g nitram/lys. The total NO_3-N loss over the period in the leachates ranged from 0.02 ± 0.01 g N/lys (ryegrass/clover mixture at zero N application) to 1.58 ± 0.14 g N/lys (wheat at N fertilizer application of 19.67 g nitram/lys) (Fig 5.3.4-2).

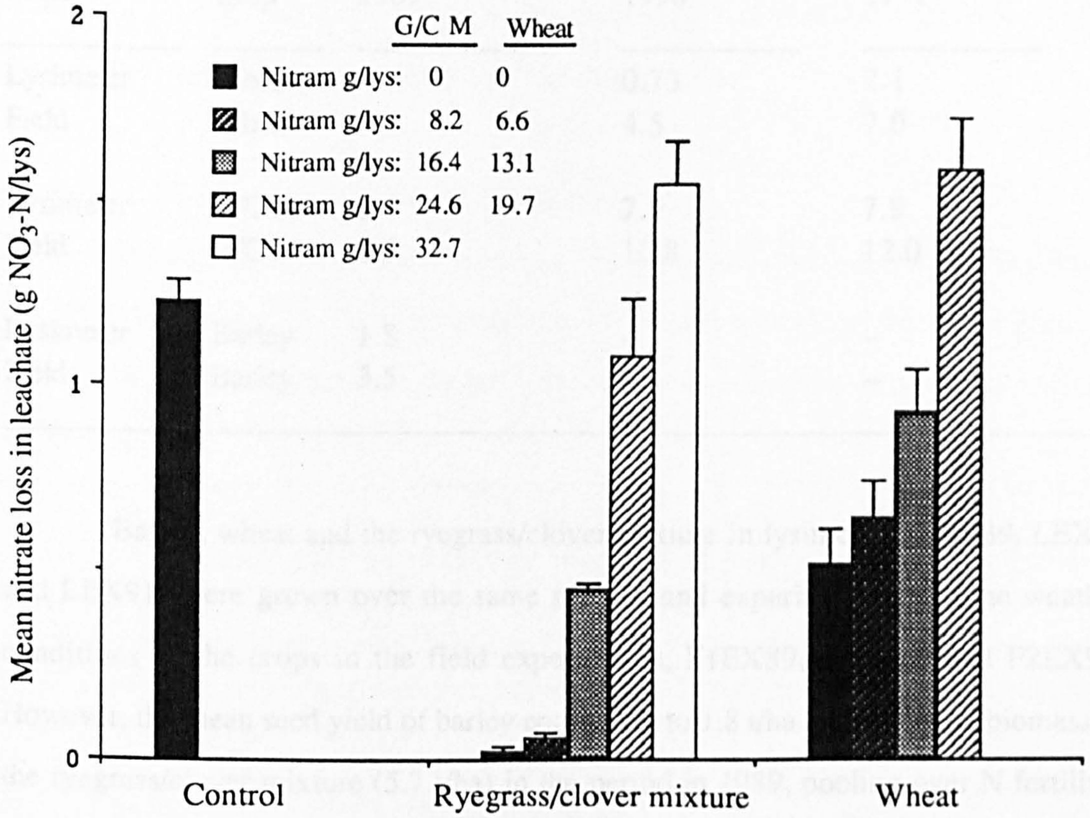

Fig 5.3.4-2. Comparison of total nitrate loss in the leachate over the period from 15th April 1989 to 13th October 1991 between the crops and fertilizer application. Confidence limits are standard errors of the mean. N fertilizer levels refer to materials and methods in this chapter. LSD = 0.28 g N/lys.

5.4 Discussion

(1) Yield performance of the crops

Table 5.4-1 compares the yields of barley, wheat and the herbage mixture observed in this lysimeter experiment and in the field plots described in the previous chapters.

Table 5.4-1. Comparison of mean yield (t/ha), pooled over fertilizer application, in lysimeter and field experiments over 1989 - 91. G/C M = ryegrass/clover mixture.

Place	Crop	1989	1990	1991
Lysimeter	Wheat	--	0.73	2.1
Field	Wheat	--	4.5	7.0
Lysimeter	G/C M	5.7	7.9	7.9
Field	G/C M	8.5	10.8	12.0
Lysimeter	Barley	1.8	--	--
Field	Barley	3.5	--	--

Barley, wheat and the ryegrass/clover mixture in lysimeters (LEX89, LEX90 and LEX91) were grown over the same periods and experienced the same weather conditions as the crops in the field experiments, F1EX89, F2EX90 and F2EX91. However, the mean seed yield of barley equivalent to 1.8 t/ha and the mean biomass of the ryegrass/clover mixture (5.7 t/ha) in the period in 1989, pooling over N fertilizer application, were much lower than the corresponding yields for barley (3.5 t/ha) and the ryegrass/clover mixture (8.5 t/ha) from the field trial in the same year.

Similarly in 1990 and 1991, lysimeter grown crops yielded less than their field counterparts. Wheat yields were on average 16% and 30% of those observed in the field, whilst for the ryegrass/clover mixture they were 66 - 73% of field yields.

The lower yields obtained in the lysimeter may be caused by the restriction of water supply since the roots of the crops were limited by lysimeter depth but in field conditions they may extend as deep as 90 cm for wheat (Quisenberry and Reitz 1967), 90 cm for barley and 80 cm for herbage grasses (Hansson, Andren and Steen 1991). Another possible cause of yield reduction may be lowered water availability during dry periods since water in drainage through lysimeters may leave the soil root zone permanently whereas in field conditions water movement from subsurface reserves may diminish soil water deficits in the soil root zone (Russell 1982).

The different patterns of rainfall distribution in 1990 and 1991 may be the reason why the ryegrass/clover mixture maintained yield in lysimeter but wheat did not. Over wheat growth season (May to July), 127 mm rainfall in 1990 was 66% of that in 1991. But 318 mm rainfall in 1990 over the main growth season (May to October) of the ryegrass/clover mixture was 14% more than that in 1991.

(2) Crop yield responses to N fertilizer

Equation (10) gave a good fit to all data from both lysimeters and field plots, $R^2 > 0.99$ in all instances. To summarize the different responses of the crops grown in lysimeters from those grown in the field, the economic responses of the crops are listed in Table 5.4-2.

Table 5.4-2. Comparison of economic response of the crops grown in lysimeter (LEX89, LEX90 and LEX91) and in field experiments (F1EX89, F2EX90 and F2EX91) over the same period, data estimated from the response equation. B = barley, W = wheat, G/C M = ryegrass/clover mixture, N_e = N fertilizer for economic response, Y_e = yield of economic response.

		Grown in lysimeter			Grown in field		
Crop	From - To Month/year	N_e kg/ha	Y_e t/ha	Y_e/N_e kg/kg	N_e kg/ha	Y_e t/ha	Y_e/N_e kg/kg
B seed	4/89 - 7/89	47.2	1.8	38.1	112	3.7	33.0
G/C M	4/89 - 10/89	378	6.5	17.2	338	9.6	28.4
W seed	10/89 - 7/90	142	0.68	4.8	219	4.8	21.9
G/C M	10/89 - 10/90	346	11.9*	34.4	280	12.2	43.6
W seed	10/90 - 7/91	189	1.9	10.1	273	8.6	31.5
G/C M	10/90 - 10/91	425	9.0	21.2	245	12.4	50.6

* The highest yield recorded.

In five cases, Y_e/N_e ratio in lysimeter was lower than corresponding values from the field. This may reflect the fact that crops in lysimeters probably experienced less favorable growth conditions other than nitrogen deficiency when nitrogen was available or could not fully utilize the applied nitrogen because nitrate was more readily leached from lysimeters.

Contrastingly the Y_e/N_e of barley in 1989 was higher in lysimeters than in field plots. This may result from a high rate of soil nitrogen mineralization due to soil disturbance (Lowrance, Stinner and House 1984) when the soil was first placed in the lysimeters. The extent to which factors determining nitrate concentration of the leachate in lysimeter experiment differed from those occurring in field conditions is unknown. Together with the noted lower yields, it is clear that the lysimeters used in the experiment did not mimic field conditions closely.

(3) Effects of the crops on leachate volume

The differences in crop growth and water status of the soil in lysimeter may determine the volume and nitrate concentration of leachate in two ways. Firstly, the lowered yield in both crops in lysimeter may result in less nitrogen fertilizer uptake leaving higher nitrate levels in the soil for subsequent leaching. Secondly, since crop growth in lysimeters was reduced, and by inference water utilization also, the total volume of soil water containing nitrate available for leaching in lysimeters may have exceeded the corresponding volume occurring in the field.

It is well known that growing crops need an adequate supply of water either via rainfall or irrigation principally to meet the transpiration loss, which may range from 2 - 6 mm of water per day in summer (Harper 1983). In this lysimeter study, natural precipitation provided the only water for crop growth. Over the period April 1989 to October 1991, no leachate was found from April to September in each year from the lysimeters under crops. Transpiration and evaporation are the likely causes of the utilization of the entire volume of rainfall receipts in these periods of active crop growth. Leachate was collected from the lysimeters of the control treatment in August, September and October in 1989, in May and June 1991. Most leachate was collected over the periods November 1989 to February 1990 and October 1990 to March 1991 from all treatments which is to be expected because of high winter rainfall.

The small volume of leachate collected in September 1989 (Fig 5.3.1-4) from four out of fifteen lysimeters under the ryegrass/clover mixture is difficult to account for. It may be due to uneven or lack of compaction of the soil structure in lysimeter during the first year of the establishment of soil profile.

The experiment indicated the importance of yearly variation, the different effects of wheat and the ryegrass/clover mixture as well as the effects of N fertilizer application on leachate volume. The general tendency for an inverse relationship between biomass and leachate volume, is illustrated in Fig 5.4-1.

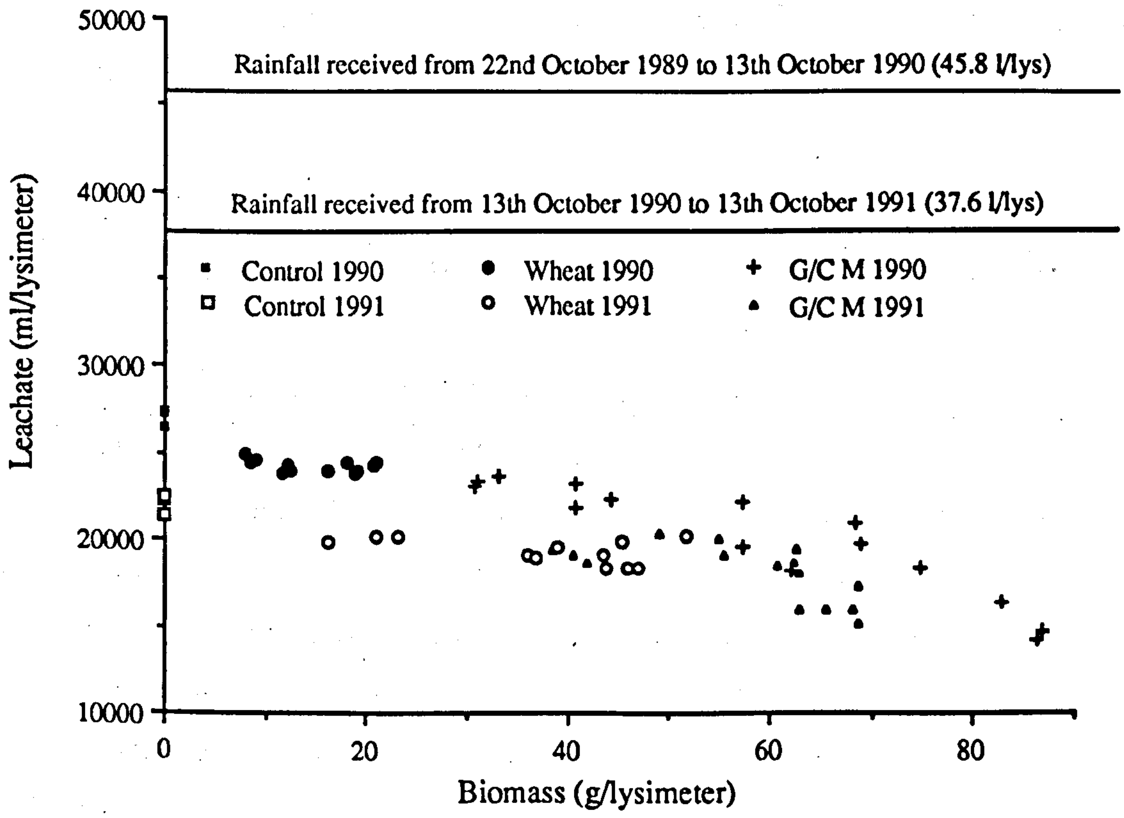

Fig 5.4-1. The relationship between leachate volume and biomass from 22nd October to 13th October 1991. (lys = lysimeter).

The yearly variation in leachate may be explained by the relative volume of rainfall and its distribution. In 1990, there was a severe drought (only 125.1 mm of rainfall) from March 1990 to July 1990, which is the main growth period of autumn sown wheat. As a result, the biomass and seed yield of wheat in this season (LEX90) was drastically reduced, which may, in turn, determine the future pattern of water utilization, limited vegetation resulting in higher drainage in later wetter parts of the season. In contrast, the ryegrass/clover mixture by virtue of a longer growing period maintained yield, which could, therefore, reduce leaching.

In contrast to 1990, the rainfall (191.3 mm) from March to July in 1991 was favorable to the growth of the wheat during its main growing season, although there was a short period of drought with only 10.8 mm of rain from the 1st to the 31st of the May in 1991.

The results imply that different growth patterns of the crops might differ the patterns of water usage and finally affect the volume of leachate.

The effect of nitrogen fertilizer on reducing the volume of leachate might presumably be a consequence of stimulated biomass which would result in increased transpiration.

(4) Effects of crops and N fertilizer application on nitrate concentration of the leachate

Although the absolute volume of water passing through the soil profile may be the main factor which leaches nitrate from arable soils in non-irrigated farming systems, the central problem related to cropping and N fertilizer use is the nitrate concentration of the leachate. The factors, which may influence nitrate concentration in leachate, may be grouped into four categories, namely soil type, climate, cropping system and N fertilizer application (Strebel, Duynisveld and Bottcher 1989). Of these, soil type and climate are usually site-specific factors though soil organic matter is influenced by past cropping system (Garwood, Tyson and Clement 1977). Cropping system and N fertilizer application as factors influencing nitrogen content of leachate are most important in arable ecosystems in comparison to grassland.

The extent to which a crop may influence the nitrate concentration of leachate is related to the duration and time of a soil cover that the crop provided, the rate of water and nitrogen removed by growth and the soil structure and nitrogen status as influenced by rooting patterns (Goss 1991; Bottner, Cortez and Sallih 1991). The amount and the time of N fertilizer application required by the crop are additional factors enhancing effects.

The ryegrass/clover mixture in this experiment provided a soil cover all year round and took up more nitrogen from the soil than wheat or barley. Although the total amount nitrogen fertilizer applied to the herbage mixture (0 to 32.74 g nitram/lys, with five incremental levels) over 2.5-year period was higher than that of wheat or barley (0 to 19.67 g nitram/lys with four incremental levels), the average nitrate concentration of the leachate from the herbage crop (18.5 ± 5.1 mg NO_3-N/l) was lower than that under wheat or barley (20.0 ± 3.0 mg NO_3-N/l). The result agreed with the general tendency of nitrate leaching under these two cropping systems (Cooke 1984).

The weighted mean nitrate concentration under the ryegrass/clover mixture (11.6 ± 0.14 mg NO_3-N/l/ at a N fertilizer level of 258 kg N/ha/year) from this experiment was close to the result described by Hood (1974) for ryegrass at 250 kg N/ha. The weighted mean nitrate concentration (50 ± 2.3 mg NO_3-N/l) under the ryegrass/clover mixture at a N fertilizer level of 515 kg N/ha/year was higher than that (35.5 mg NO_3-N/l) at 750 kg N/ha reported by Hood (1974). The discrepancy, 50 mg NO_3-N/l as opposed to 35.5 mg NO_3-N/l may be caused by lower yielding of herbage due to the limitations of shallow lysimeters.

The weighted mean nitrate concentration under wheat or barley (14.8 ± 2.3 mg NO_3-N/l at N fertilizer level of 103 kg N/ha) was marginally higher than the 4 - 11 mg N/l for barley at 125 kg N/ha fertilizer level reported by Shaw and Jones (1974). The high nitrate concentration observed under wheat may be a reflection of the failure of crop growth as indicated extremely low yield (0.73 t/ha) over the range of fertilizer applied, 0 to 300 kg N/ha (Fig 5.3.3-5A). The high nitrate concentration detected on 18th October, 6th November and 5th December 1990 under wheat are amongst the high concentration reported in the literature (Wong, Wild and Juo 1987).

The nitrate concentration of the control (24.1 ± 1.1 mg NO_3-N/l/2.5-year) in this experiment fell in the range (10.4 - 40.0 mg N/l) from the lysimeter studies of Shaw and Jones (1974).

Nitrogen fertilizer application appeared to have two major effects on the nitrate concentration of the leachate. Firstly and obviously, it added nitrate to the soil, which was likely to be leached out if not taken up by plants. Secondly, it stimulated the yields of the crops which, in turn, reduced the volume of leachate. These two effects, however, were likely to increase nitrate concentration of the leachate. The range of nitrate concentrations found in this study was similar to that reported by Garwood and Tyson (1973), except for the two cases of extremely high concentration (167.9 ± 59.2 and 217.1 ± 24.8 mg NO_3-N/l) recorded on 22nd November 1989 (Fig 5.3.2-5A). This unusual high concentration may be the result of high rate of N fertilizer application (10.94 and 14.60 g nitram/lys respectively) coupled with relatively lower yield in 1989 (49.4 and 48.7 g DM/lys respectively). Lack of compaction of the soil profile in the specific lysimeters relating to these observations may have also contributed to excessive leaching.

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CHAPTER 6 GENERAL DISCUSSION

6.1 Crop yields, economic value and practical considerations

In most farming systems, there are two primary goals of production, provision of food for the increasingly large human population and raw materials (including animal feed stuffs) for the needs of other industries. These two basic requirements of human society are always a driving force in agricultural development (Li 1982). In the philosophy of the development of agricultural thinking, the recently emerged idea of sustainable agriculture is a logical extension of these two primary goals and emphasizes the need for security of a long-term food supply from sustainable production systems. The reason for this may be partly explained by the current world situation of the balance of food supply and human population growth.

Whilst global food production has paralleled world human population growth in terms of food per capita (Pirie 1975), the achievements in agricultural development over the last thirty years are remarkable, in spite of the economically uneven distribution of available food which has failed to reach people in poverty (Hillary 1984). But the shadow of potential hunger and food shortage has always kept pace with increases in world food production. Despite over 300 million tonnes of grain reserves in the developed countries, over 500 million people were chronically hungry towards the latter 1980's and 13 - 18 million people die from hunger or hunger related diseases each year (World Commission on Environment and Development 1987). The food problem is already acute in Asia, Latin America and Africa (Conway and Barbier 1990). Moreover, in a thorough analysis of the possibilities for expanding agricultural production, the Food and Agricultural Organization of the United Nation came to the conclusion that the self-sufficiency ratios of nearly all commodities would fall in developing countries towards the year 2000 (Spedding 1983).

It is clear that great effort needs to be put into continuing to increase yields. The question remains: can this objective be achieved under constraints of resource input and with less potential risk of nitrogen leaking into water sources. One case study, has shown that this objective is achievable if available resources are carefully organized and the appropriate technology is employed (Guo and Bradshaw 1992).

The results from the experiments reported in this thesis have demonstrated that an increase of dry matter yield or crude protein yield per hectare is clearly possible by the selection of suitable field crops (Table 6.1-1) and nitrogen application rates.

Table 6.1-1. A summary of the economic yield of crops in the absence of N fertilizer and the estimated economic response (to nitrogen) using data (mean ± SEM) from experiments (F1EX89, F1EX90*, F2EX90 and F2EX91) in Chapters 2 and 3. YNN = economic yield in the absence of N fertilizer, CPNN = crude protein yield in the absence of N fertilizer, EN = level of N fertilizer required for the economic response, YEN = yield achieved with N at the economic response, HID = harvest index, CPEN = crude protein yield at EN.

Crop	YNN (kg/ha)	CPNN (kg/ha)	EN (kg N/ha)	YEN (kg/ha)	HID (%)	CPEN (kg/ha)
Barley	2985	379	112	3726	0.360	473
Wheat	3530 ± 142	408	246 ± 27	6728 ± 1893	0.423 ± 0.001	778
Lupin	2248 ± 960	850	67 ± 16	2702 ± 1068	0.400 ± 0.007	1022
Rape	968 ± 383	220	293 ± 44	2082 ± 101	0.210 ± 0.022	472
G/C M	7874 ± 1170	1403	259 ± 35	11924 ± 828	1	2124

* Yields of barley, lupin and rape were not included.
G/C M = ryegrass/clover mixture.
Standard errors of means are calculated over years, where data is available.

Table 6.1-1 clearly shows that the ryegrass/clover mixture in comparison to other crops gives the highest dry matter yields and crude protein yield both with no N fertilizer addition and with N fertilizer applied optimally. The reason for this is largely explained by the use of a harvest index of 100%. The second highest crude protein yield was given by lupin, being associated with relatively lower yield of seed (YEN). Barley and rape gave the lowest crude protein yield but only in rape was this accompanied by low YEN. The lowest economic yield was observed in rape but since this is calculated on the basis of the mean of the yields harvested in 1989 and 1990, it is depressed because of the drought in 1990. Wheat gave an intermediate crude protein yield but the second highest economic yield both in the absence of and at optimal nitrogen fertilizer indicating the relatively high yielding capacity of a cereal crop.

The production of a farming system is governed ultimately by the economic practices of current economic thinking. The objective of growing crops in most farming systems is mainly for trade nowadays. Thus the economic value of a crop is of paramount importance. In this study it is, however, impossible to assess the detailed economics of production since this would involve estimating the full cost of production of wheat, barley, rape, lupin and the ryegrass/clover mixture, include the inherent difficulties of allocating fixed cost (rent and rates, labor, machinery and power, general overhead) and variable costs (fertilizers, pesticides and herbicides, seeds). Also a detailed economic evaluation is complicated by seasonal variation in the fodder quality of the herbage mixture and yearly variation in the quality for barley, wheat, rape and lupin grains. Changes in commercial market costs also tend to make such analysis retrospective. As an alternatively, it may be argued that estimates of the gross sale value of the products and the cost of N fertilizer, using average prices may highlight the differences amongst the crops. Table 6.1-2 gives this comparison.

Table 6.1-2. Gross sale value of the crops and the cost of N fertilizer, using estimated yields (Table 6.1-1) and the product price (Table 1.4-4). SV1 = sale value of yield in the absence of N fertilizer, ENC = cost of N fertilizer for the economic response, SV2 = sale value for yield at the economic response. G/C M = ryegrass/clover mixture.

Crop	SV1 (£/ha)	ENC (£/ha)	SV2 (£/ha)	(SV2 - SV1)/ENC
Barley	419.24	35.71	523.32	2.91
Wheat	531.87	78.43	1013.71	6.14
Lupin	480.96	21.36	578.09	4.55
Rape	228.70	93.42	491.89	2.82
G/C M	1188.66	82.58	1800.05	7.40

In the absence of nitrogen fertilizer and at the level required for the economic response, the sale values of the crops in rank order were the ryegrass/clover mixture > wheat > lupin > barley > rape. The ratio of (SV2 - SV1)/ENC in Table 6.1-2 is the monetary return from increased yield per unit cost of N at the level required for the economic response. On this basis a similar ranking of crops is achieved. After estimating the gross sale value of the products, the profit or net economic return depends on the cost of the production. In arable crop production systems, total fixed cost is commonly relatively constant (Cooke 1984), and lower than that of grass production (Nix 1980). The average fixed cost in 1980 ranged from £309/ha to £329/ha in cereal farms and £490/ha to £530/ha in dairy farms (Cooke 1984). The average fixed cost of £513/ha for dried grass production in 1975 (Nix 1980) falls in the range for dairy farms. It is reasonable that the fixed cost for dried grass production may be two-thirds more than that for arable crops because of the high machinery costs used for drying fresh grass (Nix 1980). However the high quality feed it provides makes it economically comparable with other production systems.

Lupin is a relatively new crop to the U.K., which has not achieved a stable production system and market yet. The yield and sale value mentioned above shows that the potential value of the lupin crop is quite attractive both in providing protein for animal feed stuff or economic value return to farmer. Whether or not lupin may form a reliable production system and create a steady market largely depends on its reliability of production and the consistent and satisfactory seed quality. To date lupin yields in the U.K. have shown predictability. However if the anticipated global climate changes are realised then lupin may find a market niche in the U.K..

6.2 Effect of N fertilizer on crop yield and economic value

Optimization of nitrogen fertilizer application is a central issue in modern agricultural production systems and many self-sufficient farming systems (Frissel 1978). One of the reasons for this is that nitrogen fertilizer is an energy consumptive product from synthetic chemical processes. Although the overall energy for reduction of N_2 to NH_3 gives a net energy release, the initial breakdown of the stable chemical bond ($N \equiv N$) requires an energy of 340 KJ per mole of NH_3. With the thermodynamic efficiency of 50% which can be achieved at the present day (Mahon 1983), plus the energy used for packing and transportation, the total energy usually spent on one kg of

N fertilizer that finally reaches point of use is 57 million joules (Pimentel and Pimentel 1979; Pimentel 1980).

Neither is the biological fixation of N_2 cheap in terms of energy consumption. The initial energy requirement of 316 KJ for cleaving the N≡N bond per mole of NH_3 is inevitable (Mahon 1983). Taking into account a metabolic efficiency rate of 40%, nodule maintenance and unfavorable conditions in field, as much as 15 to 20 g carbohydrate (233 to 311 KJ) is needed to make one g of N available to a plant (Russell 1961). Although Ryle (1983) estimated the cost of one g of fixed N to be 6.4 to 9.6 g of glucose, Mahon (1983) in reviewing a range of experiments concluded that an average of 11 g carbohydrate was necessary. Given this conclusion and if the biological efficiency is defined as the theoretical energy (316 KJ) required for breakdown of the N≡N chemical bond per mole of NH_3 divided by the average energy (2390 KJ) used for N fixation, the average overall biological efficiency is estimated at only about 13%. This may explain why all legume crops have a much lower dry matter yield than cereal crops.

On the other hand, it is widely accepted that the present production of nearly all cereal crops and oilseed rape needs to be supported by nitrogen fertilizer application otherwise yields will fall (Cooke 1984). Taking the U.K. as an example, the consumption of nitrogen fertilizer has grown from zero in 1837 to about 1.39 million tonnes in 1982 (The Royal Society 1983). The cost of fertilizer (including P and K) (Cooke 1984) ranges from £24.00/ha in winter wheat to £100.00/ha in potato production (1975 data). This reflects a monetary investment ranging from 11.9% of the total cost in wheat to 16.4% in sugar beet production (Briggs and Courtney 1985). Cooke (1984) cited an expenditure of £58.39/ha on N fertilizer alone in barley production in 1981, which accounted for 30.9% of the variable cost of production.

It is clear therefore that there is, so far, no cheap way to supply crops with nitrogen as plant nutrient both in terms of energy consumption and monetary investment and only optimal use of nitrogen may minimise total cost (fossil fuel, biological energy and monetary investment) and raise the yield simultaneously.

The optimization criteria varies according to viewpoint. To a farmer optimization of N fertilizer application may equate directly to the economic response. To an ecologist, the potential risk of nitrate leaching must also be taken into consideration. To those suffering food shortages, the 'optimization' is equivalent to the maximum yield response to N fertilizer.

In this thesis economic response has been considered to be the optimal response. The results of the experiments described in Chapters 2 and 3 illustrated that the optimal level of N fertilizer is lowest in lupin and highest in oil seed rape.

To compare all crops, however, the four following indices are useful.

i). nitrogen-yield efficiency (N-Y E) is defined as:

$$\text{N-Y E} = \frac{[\text{Yield receiving N}] - [\text{Yield receiving no N}]}{\text{kg N applied}}$$

ii). the nitrogen-economic efficiency (N-E E) is defined as:

$$\text{N-E E} = \frac{\begin{bmatrix}\text{Sale value of products}\\ \text{receiving N (£)}\end{bmatrix} - \begin{bmatrix}\text{Sale value of products}\\ \text{receiving no N (£)}\end{bmatrix}}{\text{N fertilizer cost (£)}}$$

iii). the nitrogen-protein yield efficiency (N-P E) is defined as:

$$\text{N-P E} = \frac{\begin{bmatrix}\text{Crude protein}\\ \text{yield receiving N}\end{bmatrix} - \begin{bmatrix}\text{Crude protein}\\ \text{yield receiving no N}\end{bmatrix}}{\text{kg N applied}}$$

iv). apparent N recovery is defined as:

$$\text{\% recovery of N} = \frac{\begin{bmatrix}\text{N harvested in crop}\\ \text{receiving N (kg/ha)}\end{bmatrix} - \begin{bmatrix}\text{N harvested in crop}\\ \text{receiving no N (kg/ha)}\end{bmatrix}}{\text{N fertilizer added (kg/ha)}}$$

Table 6.2-1. Comparative assessment of crops using indices described in the text at the optimal N fertilizer application, data (mean ± SEM) estimated from the N response curves and pooled over the experiments (F1EX89, F1EX90*, F2EX90 and F2EX91) in Chapters 2 and 3. EN = N fertilizer level for obtaining the economic response, N-Y E = nitrogen-yield efficiency, N-E E = nitrogen-economic efficiency, N-P E = nitrogen-protein efficiency.

Crop	EN (kg N/ha)	N-Y E (kg/kg N)	N-E E (£/£ N)	N-P E (kg/kg N)	Apparent N recovery (%)
Barley	112	7.6	2.91	0.84	37.9
Wheat	246 ± 27	13.0	6.14	1.50	32.6
Lupin	67 ± 16	6.8	4.55	2.57	50.2
Rape	293 ± 44	5.8	2.82	0.86	23.3
Ryegrass/clover	259 ± 35	15.6	7.40	2.78	44.5

* Only the yield of the ryegrass/clover mixture in this year is included here.

Table 6.2-1 shows that in rank order of N-Y E ryegrass/clover mixture > wheat > barley > lupin > rape. The N-E E gives a similar rank order except that lupin is greater than barley. A different rank order was found in terms of N-P E, where ryegrass/clover mixture > lupin > wheat > rape > barley. Table 6.2-1 also shows that all the crops apparently recovered less than 50% of applied nitrogen in their above ground biomass.

The ryegrass/clover mixture gave the highest efficiency in terms of N-Y E, N-E E and N-P E.

Lupin had the highest apparent recovery rate of applied nitrogen, which may imply that as a legume crop it also could use nitrogen fertilizer as a source of nutrient more efficiently than cereal crops and ryegrass/clover mixture. This characteristics emphasises the potential importance of lupins in arable cropping systems.

Another noticeable feature of the apparent recovery rate of nitrogen fertilizer from the experiments in this thesis is that all the crops had a relatively low rate if comparison is made with other reported average apparent recovery rate for instance 47 - 60% in barley and wheat (Cooke 1984), 27 - 32% in rape (Szmigiel 1982) and 53 - 67% in a ryegrass/clover mixture (The Royal Society 1983). The lower recovery rates may be explained by the relatively dry weather when the experiments were conducted. Strong evidence has been found that the apparent recovery rate is improved with increasing rainfall during the growing season of ryegrass (Morrison, Jackson and Sparrow 1980). Another possible explanation for the discrepancy is that these data make the comparison of individual cultivars with a pooled mean.

In farming practices, an improvement in the efficient use of nitrogen fertilizer depends on various factors such as management, crop species and variety and environmental variables including other plant nutrients available in soil (Whitehead 1970). For instance, the response of perennial ryegrass to fertilizer nitrogen is influenced by identifiable factors contributing to water supply (rainfall over the growing season and soil available water capacity) and yield was dependent on the uptake and recovery of fertilizer N which was also affected by water conditions (Morrison, Jackson and Sparrow 1980).

The yield response curves to nitrogen reported in Chapters 2 and 3 illustrated to some extent the variability that may occur, and which in this instance may be largely put down to variation in climatic factors. Whilst the use of an empirical model such as equation (10) enables the range of response to be described, underlying growth mechanisms are not considered. Any explanation of the differences due to climatic factors must necessarily involve an understanding of the role of N in the growth and development of plants as controlled by abiotic variables. Synthesis of this understanding into mechanistic models is clearly an important next step (France and Thornley 1984).

6.3 Effect of crop and N fertilizer application on nitrate leaching

The pattern of nitrate leaching at the experimental site was characteristically high in winter and early spring and a high concentration of nitrate was observed in October, November and December. This pattern is common in the U.K. (The Royal Society 1983). The results in this thesis suggested that an annual ground vegetation cover which allows a continuous uptake available nitrogen from soil is a crucial factor in reducing the potential risk of a high concentration of nitrate in leachate. The relative high nitrate concentration (above 11.3 mg NO_3-N/l) in the leachate of the control lysimeters (Chapter 5) and the treatment under wheat and barley receiving no N fertilizer application implied that a high rate of nitrate accumulation from mineralization of soil organic matter is a risk during dry seasons or after cereal crops have been harvested.

Herbage mixtures can easily establish an annual ground cover which results in lowering of the leaching rates of applied N and soil mineralized nitrogen. The results of this work suggest that with a ryegrass/clover mixture, an annual application of 300 kg N/ha would keep nitrate concentration below the upper limit of World Health Organization's safe level (11.3 mg NO_3-N/l).

In agroecosystems, nitrogen cycling is greatly influenced by the biological structure, in the sense of the time and space of distribution of crops and animals (Guo and Yuan 1987). Different cropping systems are characterized by their own features of nitrogen translocation, utilization and loss (Pate and Farquhar 1987). Thus, to achieve a reduction of nitrate concentration in leachate and maintain economic performance is not easy, especially if it involves a change of farming system. On the other hand, there is evidence that N leaching rate may be reduced on arable land if the appropriate technology is chosen to match N availability in the soil with crop needs and to avoid over fertilization (Neeteson 1985; Papendick 1987). This thesis points to the continuing need to quantify and understand the variation in crop response to nitrogen and the fate of nitrogen in soils.

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Appendix A Analytical methods

A.1 Method of nitrogen assessment

A.1.1 Digestion of plant and soil materials

Dried plant material ground to pass 2 mm sieve and dried at 65^0 C for 24 hours before the sample was weighed out for digestion.

0.15 g plant tissue in cereal grain, root and straw, 0.1 g plant tissues in ryegrass/clover mixture and 0.05 g plant tissues in lupin seed and rape seed were weighed out into an acid-washed digestion tube using a micro-balance. The samples are digested by 3 ml concentration (18 M) sulphuric acid in the presence of one Kjeldhal catalyst tablet (contains 1.0 g K_2SO_4 and 0.1 g $CuSO_4$) for 1 hour at 150^0 C and followed by approximate 3 hours at 350^0 C till the solution is clear. After cool, make the digestion up to 100 ml and store in bottle prior to analysis.

Digestion 1.0 g of air-dried soil (passed 2 mm sieve) in 5 ml sulphuric acid as above in plant materials, and the digestion was made up the same volume and stored in same way as above.

The solution of the sample after digestion should be analysed on the Technicon Autoanalyser using the Ammonia-N manifold.

A.1.2 Extractable procedures and preparation of leachate

Weigh out 2 g air-dried soil (passed 2 mm sieve) into a 150 ml conical flask and shake with 40 ml of 6% sodium chloride for 30 minutes. Filter through a Whatman 42 filter paper and store filtrate in a fridge prior to analysis.

Filter leachate through a Whatman 42 filter paper and store filtrate in a fridge just above 0^0 C prior to analysis.

The extraction and the leachates should be analysed on the Technicon Autoanalyser using the Ammonia-N manifold for ammonia-N and using the Nitrate/Nitrite manifold for nitrate-N.

A.1.3 Analysis ammonia-N (NH_4-N) after digestion

Nitrogen in plant and soil material after digestion was converted to ammonia-N and can be measured with a Technicon Autoanalyser at 625 nm. The system operates at 50 samples per hour using a 4:1 (sample:wash) ratio. The reagents used in this procedure are as follows:

Alkaline phenate: Dissolve 135 g of sodium hydroxide in 500 ml distilled water, cool the solution and add 387.5 ml liquified phenol (80% w/v) with stirring. Cool and dilute to one litre. Allow to stand 12 hours before use.

Sodium hypochlorite: Dilute sodium hypochlorite solution (12 - 14% available chlorine) to give a strength of 1.5% available chorine.

1 N Sulphuric acid: Dilute 28 ml concentration (18 M) sulphuric acid to one litre with distilled water.

EDTA 1: Dissolve 2 g EDTA disodium salt and 1 g sodium citrate in one litre of distilled water. Add 3.5 g sodium hydroxide and check pH is between 12.45 and 12.55. Add more sodium hydroxide as necessary.

Standard stock solution: Dissolve 4.7162 g ammonium sulphate in one litre of 1 N sulphuric acid to make 1000 ppm (NH_4-N) stock solution.

Standard working solution: Dilute the stock solution to a range of 0, 5, 10, 15, 20, 25, 30 ppm for calibration with 1 N sulphuric acid. First, dilute 50 ml of stock solution to 500 ml with 1 N sulphuric acid to make up 100 ppm solution. Second, serially dilute 0, 5, 10, 15, 20, 25, 30 ml of the 100 ppm solution to 100 ml using volumetric flask with 1 N sulphuric acid.

Set up Technicon Autoanalyser according to the diagram of ammonia in acid manifold and warm up the system at least for 20 minutes before running samples. The result on a chart recorder is in the unit of ppm. Using following formula to calculate the N % of the air-dried plant and soil materials.

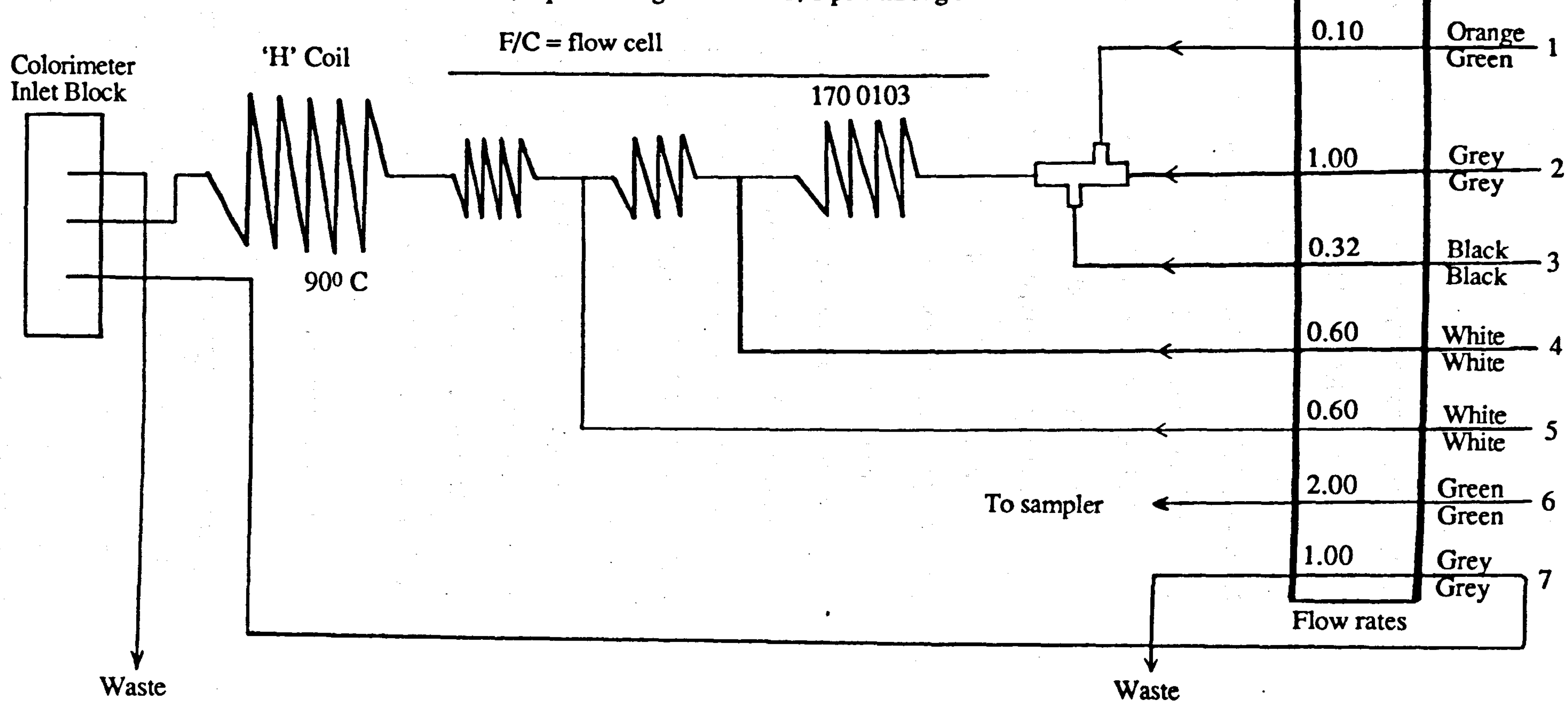
$$N\ (\%) = \frac{\text{ppm read from chart recorder}}{\text{Sample weight (g)} \times 100}$$

AMMONIA IN ACID MANIFOLD - 625 nm FILTER

Table of reagents:

	Copper catalyst 0.5 - 30 ppm	No copper catalyst 0.5 - 30 ppm
1	Sample	Sample
2	EDTA 1	Water
3	Air	Air
4	Alkaline phenate	Alkaline phenate
5	Hypochlorite	Hypochlorite
6	1 N sulphuric acid	1 N sulphuric acid
7	F/C pull through	F/C pull through

F/C = flow cell



A.1.4 Analysis ammonia-N (NH_4-N) after extraction and in leachate

Ammonia is determined by the Berthelôt Reaction in which a blue coloured indophenol-type compound is formed when the ammonium salt is added to sodium phenoxide followed by sodium hypochlorite. The sensitivity is increased by addition of sodium nitroprusside. The indophenol blue compound can then be measured with the Technicon Autoanalyser at 625 nm. The system operates at 50 samples per hour using a 4:1 (sample:wash) ratio. The reagents used in this procedure are as follows:

EDTA 1: Make up solution as previous in ammonia after digestion.

EDTA 2: Dissolve 2 g EDTA disodium salt and 1 g sodium citrate in 500 ml of distilled water. Add 20 ml of acetone and dilute to one litre. Add 0.4 g sodium hydroxide and check pH is between 10.5 and 11.0. Add more sodium hydroxide as necessary.

Hypochlorite - nitroprusside: Dilute 250 ml sodium hypochlorite solution (12% w/v available chlorine) with 500 ml water. Add 1 g sodium nitroprusside, dissolve completely and make up to one litre with distilled water. This solution may be stored for two days in dark bottle in fridge. Filter before use and keep in an ice bath while using.

Alkaline phenate: Wash 110 ml of liquified phenol (80% w/v) into a volumetric flask with distilled water, and chill the flask in an ice bath. Dissolve 36 g of sodium hydroxide in 500 ml distilled water, chill the solution in ice, and wash into the volumetric flask with stirring. Make up to one litre with distilled water. This solution should be colourless. Store in a dark bottle in fridge. Filter before use and keep in ice bath while suing.

Standard stock solution: Dissolve 3.8207 g ammonium chloride in one litre of distilled water. Add 2 drops chloroform as preservative. The concentration of this stock solution is 1000 ppm NH_4-N.

Standard working solution for soil extraction: Dilute the stock solution to a range of 0, 5, 10, 15, 20, 25, 30 ppm for calibration with 6% sodium chloride. First, dilute

50 ml of stock solution to 500 ml with 6% sodium chloride to make up 100 ppm solution. Second, serially dilute 0, 5, 10, 15, 20, 25, 30 ml of the 100 ppm solution to 100 ml using volumetric flask with 6% sodium chloride.

Standard working solution for leachate: Dilute the stock solution to a range of 0, 1, 2, 3, 4, 5 ppm for calibration with distilled water. First, dilute 10 ml of stock solution to 100 ml with distilled water to make up 100 ppm solution. Second, serially dilute 0, 1, 2, 3, 4, 5 ml of the 100 ppm solution to 100 ml using volumetric flask with distilled water.

Set up Technicon Autoanalyser according to the diagram of ammonia in water manifold and warm up the system at least for 20 minutes before running samples. The result on a chart recorder is in the unit of ppm. The NH_4-N concentration of the leachates is the direct readings from the chart recorder and using following formula to calculate the NH_4-N (ppm/100 g soil) of the air-dried soil materials.

$$NH_4\text{-}N = \frac{\text{ppm read from chart recorder}}{\text{Sample weight (g)}} \times 4$$

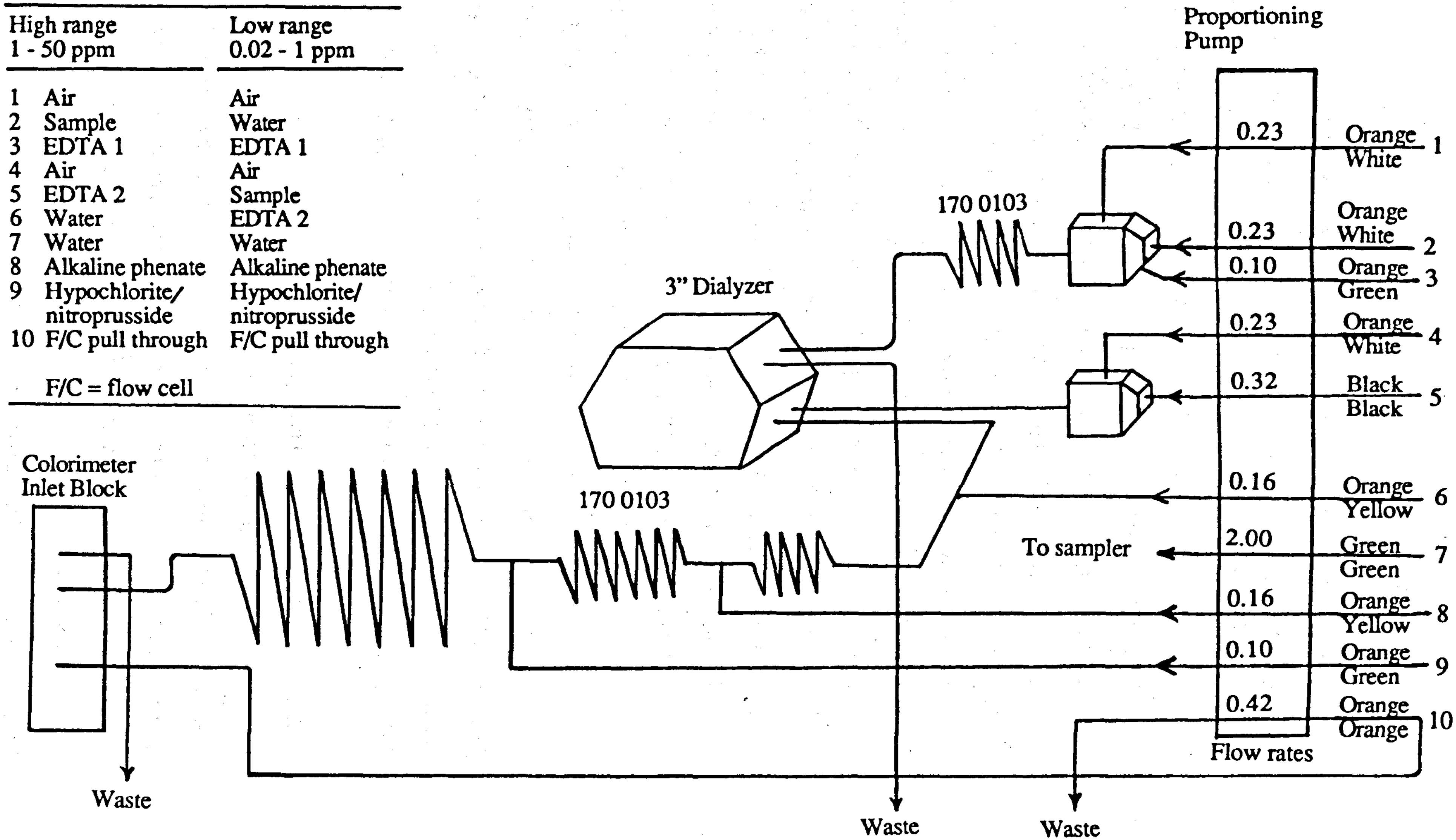
AMMONIA MANIFOLD - 625 nm FILTER
Ammonia in water

All flow rates are in ml/minute

Table of reagents:

	High range 1 - 50 ppm	Low range 0.02 - 1 ppm
1	Air	Air
2	Sample	Water
3	EDTA 1	EDTA 1
4	Air	Air
5	EDTA 2	Sample
6	Water	EDTA 2
7	Water	Water
8	Alkaline phenate	Alkaline phenate
9	Hypochlorite/ nitroprusside	Hypochlorite/ nitroprusside
10	F/C pull through	F/C pull through

F/C = flow cell



A.1.5 Analysis nitrate-N (NO_3-N) after extraction and in leachate

Nitrate is first reduced to nitrite with hydrazine sulphate under alkaline conditions, using copper ions as catalyst. The nitrite ion then reacts with sulphanilamide under acidic conditions to form a diazo compound, This compound then couples with N-1-Napthylethylenediamine dihydrochloride to form a reddish-purple azo dye which is measured at 520 nm. The system operates at 50 samples per hour using a 4:1 (sample:wash) ratio. The reagents used in this procedure are as follows:

Sodium hydroxide 0.2 N: Dissolve 8 g NaOH in one litre of distilled water.

Sodium hydroxide 0.4 N: Dissolve 16 g NaOH in one litre of distilled water.

Hydrazine copper reagent: Dissolve 1.4 g of hydrazine sulphate in about 500 ml of distilled water. Add 1 ml of a solution containing 11.7 g/litre of copper sulphate, and make up to one litre. This reagent should be made fresh daily.

Sulphanilamide reagent: Wash 10 g of sulphanilamide into a volumetric flask with distilled water, and chill the flask in an ice bath. Add 100 ml of concentrated phosphoric acid, and chill the solution in ice, ensuring all the solid has dissolved. Add 0.5 g of N-1-Napthylethylenediamine dihydrochloride and dissolve completely, and make up to one litre. This solution should be colourless, any pink colouration being due to nitrate in the phosphoric acid.

Standard stock solution: Dissolve 7.2221 g potassium nitrate in one litre of double distilled water. The concentration of this stock solution is 1000 ppm NO_3-N.

Standard working solution for soil extraction: Dilute the stock solution to a range of 0, 5, 10, 15, 20, 25, 30 ppm for calibration with 6% sodium chloride. First, dilute 50 ml of stock solution to 500 ml with 6% sodium chloride to make up 100 ppm solution. Second, serially dilute 0, 5, 10, 15, 20, 25, 30 ml of the 100 ppm solution to 100 ml using volumetric flask with 6% sodium chloride.

Standard working solution for leachate: Dilute the stock solution to a range of 0, 1, 2, 3, 4, 5 ppm for calibration with distilled water. First, dilute 10 ml of stock solution to 100 ml with distilled water to make up 100 ppm solution. Second, serially dilute 0, 1, 2, 3, 4, 5 ml of the 100 ppm solution to 100 ml using volumetric flask with distilled water. If the concentration of leachate is higher than the calibration, then a range of 0, 5, 10, 15, 20, 25, 30 ppm standard working solution should be prepared accordingly.

Set up Technicon Autoanalyser according to the diagram of nitrate/nitrite manifold and warm up the system at least for 20 minutes before running samples. The result on a chart recorder is in the unit of ppm. The NO_3-N concentration of the leachates is the direct readings from the chart recorder and using following formula to calculate the NO_3-N mg/100 g soil of the air-dried soil materials.

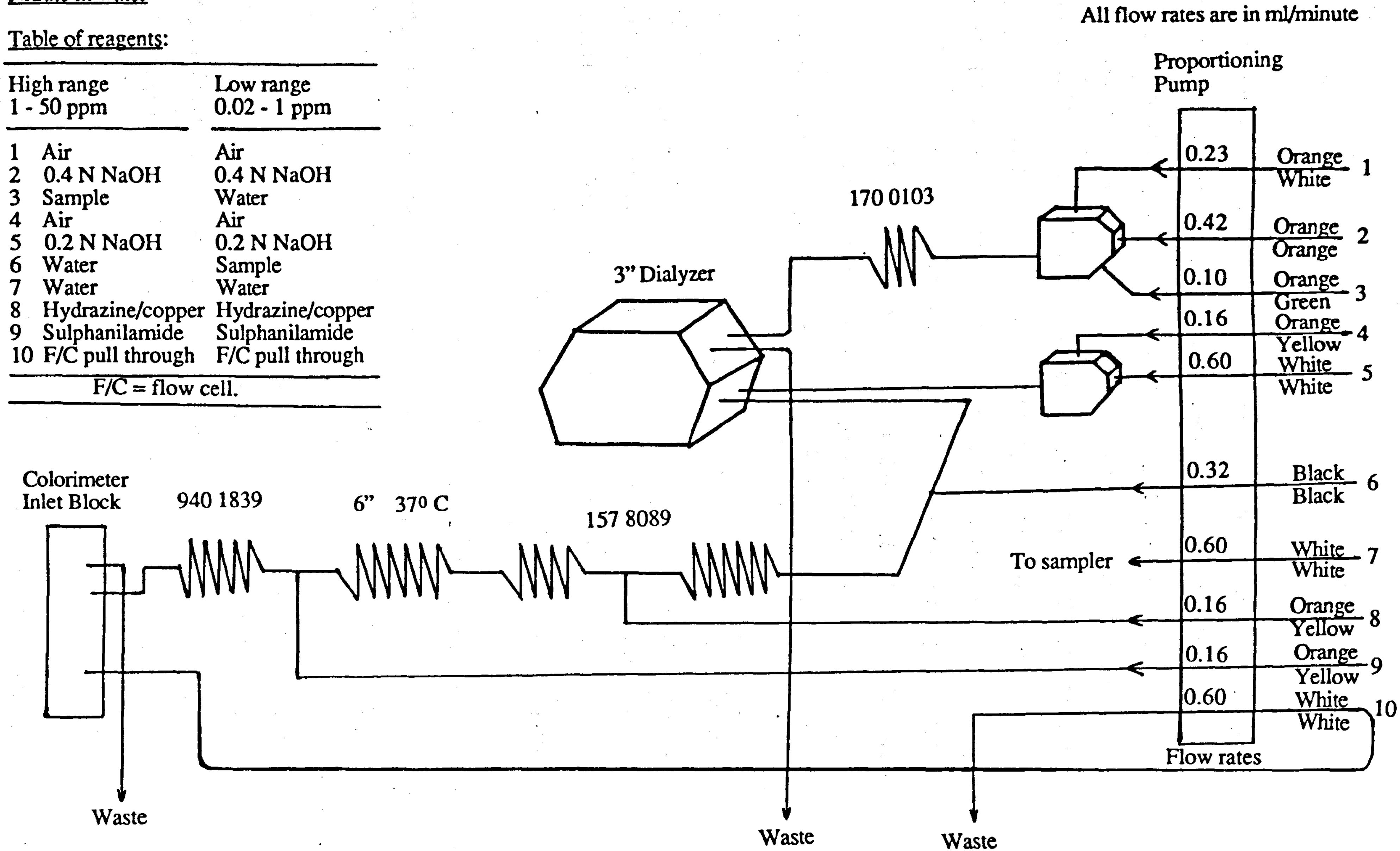
$$NO_3\text{-}N = \frac{\text{ppm read from chart recorder}}{\text{Sample weight (g)}} \times 4$$

NITRATE/NITRITE MANIFOLD - 520 nm FILTER
Nitrate in water

Table of reagents:

High range 1 - 50 ppm	Low range 0.02 - 1 ppm
1 Air	Air
2 0.4 N NaOH	0.4 N NaOH
3 Sample	Water
4 Air	Air
5 0.2 N NaOH	0.2 N NaOH
6 Water	Sample
7 Water	Water
8 Hydrazine/copper	Hydrazine/copper
9 Sulphanilamide	Sulphanilamide
10 F/C pull through	F/C pull through

F/C = flow cell.



A.2 Method of soil extractable phosphate assessment

A.2.1 Extractable procedures

Weigh out 2.5 g air-dried soil after passed 2 mm sieve into a 150 ml conical flask. Add 5 ml of charcoal and shake with 50 ml of sodium bicarbonate of pH 8.5 at 20 $\pm$ 1^0 C for 30 minutes. Immediately filter through a Whatman 42 filter paper and store filtrate in a fridge prior to analysis. Carry out a blank determination.

Sodium biocarbonate: Dissolve 42 g of sodium hydrogen carbonate in distilled water and dilute to 1 litres. Use 50% w/w sodium hydroxide solution to bring pH to 8.5 measured with a pH meter.

A.2.2 Determination of phosphate in extraction

The phosphorus in extraction was spectrophotometrically determined at 880 nm by measuring a blue complex produced by the reduction, with ascorbic acid, of the phosphomolybdate formed when acid ammonium molybdate reacts with phosphate. The reagents used in this procedure are as follows:

Ammonium molybdate 1: Dissolve 6 g of ammonium molybdate and 0.15 g of antimony potassium tartrate in 500 ml distilled water and dilute to one litre.

Ammonium molybdate 2: Dilute 250 ml of above solution to one litre.

Ascorbic acid: Dissolve 1.5 g ascorbic acid in 100 ml of distilled water.

Sulphuric acid: Add 80 ml of sulphuric acid to 500 ml of distilled water and dilute to 1 litre. The concentration of this solution is approximately 1.5 M.

Standard stock solution: Dry potassium dihydrogen orthophosphate (KH_2PO_4) at 105^0 C for 1 hour and cool in a desiocator. Dissolve 0.879 g of the dried salt in 150 ml of double distilled water and add 1 ml of concentration sulphuric acid. Dilute to 200 ml and add one drop of toluene. This stock solution is 1000 ppm (P).

Standard working solution: Dilute 10 ml of the stock solution to 500 ml with sodium bicarbonate solution to make 20 ppm solution. Serially dilute 0, 5, 10, 15, 20, 25, 30 and 35 ml of the 20 ppm solution to 100 ml using volumetric flask with sodium bicarbonate solution. This serial standard working solution ranges 0, 1, 2, 3, 4, 5, 6, 7 ppm (P) accordingly.

Pipette 5 ml of each standard working solution into a 100 ml conical flask. Add 1 ml of 1.5 M sulphuric acid and swirl the solution to assist the release of carbon dioxide. Add 20 ml of ammonium molybdate solution 2, 5 ml of ascorbic acid solution and allow to stand for 30 minutes for complete color development. Measure the absorbances in a 10 mm optical cell at 880 nm within 12 hours. Do the extraction in the same way as above and use the following formula to calculate.

$$P\ (ppm) = \frac{[\text{Read (ppm) from calibration curve - Blank}]}{\text{Sample weight (g)}} \times 50$$

A.3 Method of soil extractable potassium assessment

A.2.1 Extractable procedures

Weigh out 10 g air-dried soil after passed 2 mm sieve into a 150 ml conical flask. Shake with 50 ml of Ammonium nitrate (1 M) for 30 minutes. Immediately filter through a Whatman 42 filter paper and store filtrate in a fridge prior to analysis. Carry out a blank determination.

Ammonium nitrate (1 M): Dissolve 400 g of ammonium nitrate in distilled water and dilute to 5 litres.

A.2.2 Determination of potassium in extraction

Potassium in the extraction is determined with a flame photometer. Significant interference by other elements does not occur. The reagents used in this procedure are as follows:

Standard stock solution: Dry potassium dihydrogen orthophosphate (KH_2PO_4) at 105^0 C for 1 hour and cool in a desiocator. Dissolve 1.740 g of the dried salt in 1 M ammonium nitrate and add 1 ml of concentration hydrochloric acid. Dilute to 500 ml with 1 M ammonium nitrate and add one drop of toluene. This stock solution is 1000 ppm (K).

Standard working solution: Serially dilute 0, 4, 8, 12, 16, 20 ml of the stock solution to 100 ml using volumetric flask with 1 M ammonium nitrate. This serial standard working solution ranges 0, 40, 80, 120, 160, 200 ppm (K) accordingly.

Set the flame photometer to measure potassium emission according to the manufacturer's instructions. Nebulize the potassium working standard solutions containing 0 and 200 ppm of potassium and adjust the control until steady zero and maximum readings are obtained. Nebulize the intermediate standard solution and construct a calibration curve relating galvanometer readings to ppm of potassium. Nebulize the extraction and take the galvanometer readings. Use the following formula to calculate.

$$K\ (\text{ppm}) = \frac{[\text{Read (ppm) from calibration curve - Blank}]}{\text{Sample weight (g)}} \times 50$$

References

Allen, S. E. (1974). **Chemical Analysis of Ecological Materials.** Blackwell Scientific Pubs, Oxford.

MAFF (1983). **Fertilizer Recommendations, Agricultural and Horticultural Crop.** Bulletin 209, Ministry of Agriculture, Fishery and Food, London.

MAFF/ADAS (1986). **The Analysis of Agricultural Materials.** Third edition, reference book 427. HMSO, London.

Appendix B Methods of calculation of LSD

LSD is an abbreviate for 'Least Significant Difference', a value in statistics for testing hypothesis on comparing two means.

$$LSD_{0.05} = T_{0.05} \times \sqrt{\frac{n \times MSE}{M}}$$

Where $T_{0.05}$ is the value calculated from the 'Student' distribution at the freedom of error with confidence limit of 5%. 'n' is the number of means involved in the comparison. MSE is means square of error. M is the number of replicates on which each mean is calculated.

References

Maxwell, S.E. and Delaney, H.D. (1990). **Designing Experiments and Analyzing Data.** Wadsworth, California.

Appendix C Analysis of variance

Table C-1. Analysis of variance of dry matter yield of the crops at each harvest (experiment PE190). Fert = N fertilizer level, C = crop.

Harvest	Source	DF	Sum of squares	F	P_{HO}
1st	Crop	3	3.2425	343.2	0.0001
	Fert	1	0.0042	1.4	0.2653
	Block	2	0.0021	0.3	0.7248
	Crop*Fert	3	0.0173	1.8	0.1883
	Error	14	0.0441		
2nd	Crop	3	170.19	133.54	0.0001
	Fert	1	3.44	8.10	0.0130
	Block	2	0.01	0.01	0.9906
	Crop*Fert	3	2.75	2.16	0.1384
	Error	14	5.95		
3rd	Crop	3	66170.7	407.88	0.0001
	Fert	1	4064.6	75.16	0.0001
	Block	2	626.1	5.79	0.0147
	Crop*Fert	3	5335.7	32.89	0.0001
	Error	14	757.1		
Final	Crop	3	82099.9	88.18	0.0001
	Fert	1	6128.8	19.75	0.0006
	Block	2	4356.6	7.02	0.0077
	Crop*Fert	3	2384.6	2.56	0.0966
	Error	14	4344.9		

Table C-2. Analysis of variance of dry matter over 4 harvests with repeated measure, experiment PE190. Fert = N fertilizer level.
Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	3	38748.9	109.06	0.0027
Fert	1	5171.8	43.67	0.0001
Block	2	2030.2	8.57	0.0037
Crop*Fert	3	3520.4	9.91	0.0009
Error	14	1658.1		

Within harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	3	810529	3289.24	0.0001
Harvest*Crop	9	109695	148.39	0.0001
Harvest*Fert	3	5025	20.39	0.0001
Harvest*Block	6	2952	5.99	0.0001
Harvest*Crop*Fert	9	4202	5.69	0.0001
Error (Harvest)	42	3450		

Table C-3. Analysis of variance of relative growth rate with repeated measure, experiment PE290. C = crop, N = nitrogen fertilizer, D = density.

Between treatment effects:

Source	DF	Sum of squares	F	P_{HO}
Crop	1	0.10451	3111.84	0.0001
Fertilizer	2	0.00073	10.80	0.0002
Density	2	0.00441	65.71	0.0001
Block	2	0.00002	0.29	0.7476
C*N	2	0.00006	0.95	0.3973
C*D	2	0.00052	7.71	0.0017
N*D	4	0.00005	0.35	0.8450
C*N*D	4	0.00002	0.12	0.9744
Error	34	0.00114		
Total	53	0.11146		

Within harvest effects:

Source	DF	Sum of squares	F	P_{HO}
Harvest	5	1.2899	735.63	0.0001
Harvest*Crop	5	0.6930	396.21	0.0001
Harvest*N	10	0.0039	1.12	0.3559
Harvest*Density	10	0.0032	0.90	0.4634
Harvest*Block	10	0.0086	2.45	0.0589
Harvest*C*N	10	0.0024	0.68	0.6021
Harvest*C*D	10	0.0084	2.41	0.0620
Harvest*N*D	20	0.0073	1.05	0.4095
Harvest*C*N*D	20	0.0081	1.16	0.3376
Error (Harvest)	170	0.0596		
Total	270	2.0844		