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British Association for Bio Fuels and Oils
Recycling Carbon

LEVINGTON AGRICULTURE REPORT

Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol.

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June 2000

for the British Association for Bio Fuels and Oils (BABFO)

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SUMMARY

1. An analysis was carried out of the support energy employed and useful energy produced by oilseed rape and wheat crops grown and processed for biodiesel and bioethanol respectively. The analysis was based on current data, in particular taking into account the significant increases in crop yields and in the efficiency of fertilizer nitrogen (N) manufacture that have occurred over the past two decades.

2. A subsidiary quantification was carried out of the emissions associated with the growth of the crops. The data arising were not interpreted but are provided in this report for use in wider assessments of emissions

3. For each crop, two situations were covered: that where straw is left in the field and that where straw is removed and transported to a heat or electricity generating plant. In the latter, the energy value of the straw was taken into account

4. Where straw was left in the field, biodiesel production was strongly energy positive, giving a yield of 1 GJ biodiesel for every 0.561 GJ support energy employed (a yield/cost ratio of 1.78). For bioethanol, the yield was 1 GJ for every 0.90 GJ support energy employed (a yield/cost ratio of 1.11).

5. Where straw was burned as fuel and oil seed rapemeal used as a fertilizer, the balance was even better -yield/cost ratios were 3.71 and 2.51 for biodiesel and bioethanol respectively. In other words, for every unit of energy used to produce biodiesel, 3.71 units were made available. Utilisation of straw energy by burning is

a practical proposition .and analyses reported here indicate that it would make a strong contribution to a net energy supply from crops.

6. The analyses indicated that growth of oilseed rape for biodiesel would be energy efficient even if no credit were given to the straw. Growth of wheat for bioethanol would be strongly energy efficient only if the energy value of straw could be utilised.

7. Conclusions from the analyses are believed to be robust and conservative as the trends for increasing crop yields and for increasing energy efficiency in fertilizer manufacture are expected to be maintained and the values of some by-products (glycerol in biodiesel production and bran in bioethanol production) have not been included. If evaluation of glycerol as a fuel is successful (this is underway in Austria), the energy balance for biodiesel would be significantly improved. Indeed, the energy yield/cost ratio for the biodiesel would be raised to 2.19 (excluding straw). Indications are that future trends for energy balances in both biodiesel and bioethanol systems will be positive with biodiesel in particular becoming increasingly attractive.

TOP

1. *Introduction*

There are two main components to the total energy input to growing crops: that involved in farming operations and materials and that converted from radiant to chemical form by photosynthesis. The chemical energy content of harvested crops can exceed the energy input through farming operations and materials due to this contribution from photosynthesis. Crops can therefore act as net sources of useful energy through their utilisation of sunlight. The purpose of the analyses reported here was to determine if crops do indeed act as net energy sources in the particular situations where oil seed rape is grown for the production of biodiesel and where wheat is grown for the production of bioethanol.

Analyses take into account the energy costs for the manufacture and distribution of inputs to the crops as well as direct operations on the crops, and the energy content of the harvested crop and of the manufactured biodiesel or ethanol. -that is, life cycle analysis (LCA) approach (2, 27).

Analyses of energy use in agriculture have been conducted, many in the 1973 - 1976 period of oil shortages, but results are now outdated, technology having changed (1,5,7,8,9,18,19,23,24,25,26,31). In particular, the energy cost for manufacturing N fertilizers has reduced from 65 -75 MJ/kg N in the 1970s to 30 MJ/kg N in the most modem plants. Crop yields also have increased by 30 - 40% over the same period. The analyses reported here are based on current data.

The introduction of set-aside as a component of EU agricultural policy has made available significant areas of land for which the only agricultural use is production of non-food and non-feed crops. Oilseed rape and wheat grown for biodiesel and bioethanol are acceptable for growing on set-aside land and so put to good use land which would otherwise be wasted. Both crops can be autumn ('winter') or spring sown but yields are higher, and the choice of varieties greater, with autumn sowing. Crops grown for biodiesel or bioethanol production would almost always be autumn sown.

Straw of both crops may be ploughed into the soil (or otherwise incorporated) or baled and removed. Where there is a heat or electricity generating plant in the locality (say within 50 km), straw represents a useful energy source.

Recommendations for fertilizer p and K are adjusted to take into account the loss of these nutrients where straw is removed.

TOP

2. *Boundaries*

The following items and processes are considered here:

Crops	Relationship between yield and fertilizer N application. -- Harvested yields and energy contents. -- Loss of N following fertilizer application
Field operations	Fuel energy employed. -- Fuel consumed. -- Emissions of NOx and CO2
Fertilizers	Energy employed in mining of P & K in processing of N & P melts and in granulation of N & P. -- Losses of N & P during manufacture.
Agrochemicals/fuels/seeds	Energy expended in their manufacture
Distribution	Fuel energy employed in moving fertilizers agrochemicals and seeds from store to farm. -- Fuel energy employed in moving harvested seed or grain from farm to processing site. -- Fuel energy employed in moving straw from the farm. -- Emissions of NOx and CO2 from diesel vehicles.
Processing	Energy employed in processing rapeseed into biodiesel and of grain into ethanol

The energy employed in farm machinery and buildings and in lorries used for transport is not considered as these items would be in-place already for other purposes. Processes downstream to manufacture of biodiesel' & bioethanol are not considered. Emissions involved in the manufacture of agrochemicals and packaging and in the provision of seeds (other than those involved in transport to the farm) are not considered. These would be small relative to the main sources in vehicle operations and fertilizer manufacture.

TOP

3. *Crop production and energy output*

3.1 Yield and N input

For oil seed rape and for wheat, the main input determining yield is fertilizer N. The relationship between the amount of N applied and crop yield is quantified in field experiments where yield is measured at different rates of N application. When yield is then plotted against rate of N application, a diminishing returns curve usually emerges and this can be described by a fitted regression function. This function can then be used to calculate the economically optimum rate of N application.

Data for this report were taken from two series of trials (15 trial each on winter wheat and winter oil seed rape) funded by Hydro Agri (UK) Ltd and conducted by Levington Agriculture Ltd. Trials were conducted on commercial crops in different parts of England representative of the main arable areas In 1994 to 1998. General growing conditions for the trials were typical of good farm practice. Trial design was replicated and involved several sources of N that Hydro Agri were evaluating. Results for the standard source, ammonium nitrate (the principal source of fertilizer N used on the crops In the UK and other European countries), are used here and are shown in Table 1 for oil seed rape and in Table 3 for winter wheat. Throughout this report, rapeseed yields are expressed on a 9% moisture basis and wheat grain on a 16% moisture basis.

Offtake of nitrogen in rape (Table 2) and wheat grain (Table 4) at different rates of applied nitrogen (kgN/ha)

Mean data from these trials are typical for the two crops in the UK and are shown in graphical form in Figs 1&2 (oilseed) and Figs 3&4 (wheat). Data points are described well by fitted quadratic regression functions:

- $Yosr = 2.31 + 0.0165N - .0000369N_2$ (1)
- $Yww = 5.03 + .0344N - .0000730N_2$ (2)
- where Yosr is yield of rapeseed t/ha
- Yww is yield of wheat grain t/ha
- N is rate of applied N kgN/ha

Economically optimum rates of N application are calculated for different assumed values for the cost of fertilizer N and price of seed or grain. The relationships between optimum N rates and prices of seed or grain are shown in Fig 5 (oilseed) Fig 6 (wheat) for three assumed costs for fertilizer N. The costs of £0.3, £0.35 and £0.4/kgN are equivalent to (£1.03, £121 and £ 138/tonne of ammonium nitrate. The lowest of these prices is current (May 2000) but there is some upward pressure due to a recent series of capacity reductions in Europe.

For oil seed rape, a seed value of £120/t corresponds to an optimum N rate of approximately 180kgN/ha. This optimum is little affected by price of fertilizer N within the assumed range and, from equation (1) above, corresponds to a yield of 4.08t/ha.

For wheat, a price of £75/t corresponds to an optimum N rate of approximately 195kgN/ha at the current fertilizer N price and, from equation (2) above, to a yield of 8.96t/ha.

For present purposes therefore, it is assumed that fertilizer N applications are 180kgN/ha to winter oilseed rape and 195kgN/ha to winter wheat and that the crop yields are 4.08t/ha and 8.96t/ha respectively. At these seed and grain yields, there will be associated production of straw at 4 t/ha and 6.5 t/ha respectively (expressed on a dry-matter basis). The assumed yields are often exceeded in practice, yields greater than 5 t/ha for oilseed rape and 11 t/ha for wheat being regularly reported. There is a long standing trend for yields to increase by 1 - 2% annually..

3.2 Energy value of crop yields

One tonne of rapeseed contains typically 40 - 41% oil. Yield of oil following crushing and separation of cake is approximately 0.37 t with approximately 0.58 t of cake. On processing, the oil yields a similar amount of biodiesel with an energy value of 36 MJ/kg. If rape is grown on set-aside land, the cake produced can not be used for livestock feed. However, it is useful as an organic fertilizer with a nutrient content of 6% N, 2.7% P_2O_5 and 1.9% K_2O (29). Of these nutrients, approximately 50% of the N is available to crops in the year of application and the P_2O_5 and K_2O would be as effective as other sources where applications are for soil maintenance (the most common situation) (21). An energy credit can therefore be applied using data from section 4.2 below.

One tonne of wheat grain, on processing, yields approximately 276 kg ethanol with an energy value of 30 MJ/kg (13). There is a further 35 kg bran by-product which can be used as a fertilizer, once composted (project underway at Levington Agriculture funded by EU/HGCA). For present purposes, no energy credit is given for the bran, the quantity in any event being small.

For both oil seed rape and wheat, an energy credit equivalent to 15 MJ/kg straw is applied where the straw is removed from the field and utilised as an energy source. The energy value of oil seed rape and wheat crops is summarised in Table 5 (Energy values of oilseed rape and wheat crops).

TOP

4. *Energy costs*

4.1 Agricultural fuels

Fuel consumption figures are based on data provided by John Deere supplemented by Nix (24), and adjusted wherever necessary following review by agricultural contractors (28). It was assumed that minimum tillage techniques would be used for oil seed rape but that ploughing would be used for wheat. Wheat tends to be grown on heavier land and infestations of some weeds, notably blackgrass, are best controlled by ploughing. Table 6 shows the values assumed for the different operations that may be employed in both conventional and minimum tillage systems.

Some of these operations occur more than once during growth of a crop. There would normally be two cultivations between ploughing and drilling of wheat. Fertilizer would normally be applied on three occasions to each crop, one application of P and K in autumn followed by two top-dressings of N in spring. Spray applications would normally comprise two herbicides in autumn, insecticide in autumn, insecticide + fungicide in spring and fungicide in autumn for rape (five applications in total) and herbicide in autumn and spring and two fungicides in spring for wheat (four applications in total). The operations actually carried out in a minimum tillage system for oilseed rape and in a conventional (ploughing) system for wheat are shown in Table 7 together with related fuel consumption. It was assumed that the energy equivalent for diesel fuel is 43 MJ/l (26). The fuel energy expended in farming operations was then calculated and is shown in Table 7.

4.2 Fertilizers

The amounts of N applied are assumed to be 180 kgN/ha for oilseed rape and 195 kgN/ha for wheat (see section 3.1 above). In addition to N, there would be one application to each crop of P and K, usually in the form of a compound fertilizer blended from triple superphosphate and muriate of potash (potassium chloride). The rates of application of these nutrients should be close to those recommended in MAFF Bulletin RB209 (20) for a typical soil index of 2 for each nutrient: 50 kg P_2O_5/ha and 40 kg K_2O/ha for oil seed rape and 70 kg P_2O_5/ha and 90 kg K_20/ha for wheat where straw is removed from the field. Where straw is ploughed in, recommendations for wheat are reduced to 60 kg P_2O_5/ha and 45 kg K_2O/ha. These assumed rates of fertilizer application are similar to those reported in practice for Great Britain in 1998 (3): 204, 69 and 71 kg/ha for N, P_2O_5 and K_2O on winter oilseed rape and 183, 68 and 77 kg/ha for N, P_2O_5 and K_2O on wheat. Energy equivalents for fertilizer N (as ammonium nitrate), P_2O_5 (as superphosphate) and K_2O (as muriate of potash) have been quantified by Laegrid et al (17) on the basis of current best available technology.

For solid ammonium nitrate, production in the most modem plants involves a total expenditure of 30.5 GJ/t of N. This is much lower than estimates made around 1975 due to improvements in ammonia fixation and other process technologies. Previous generation technology involved expenditure of 46.6 GJ/t N. For present purposes, a value of 38 GJ/tN is assumed.

The mining of rock phosphate involves expenditure of 0.3GJ/t P_2O_5 but, in the most modem plants, subsequent processing into triple superphosphate involves a net release of 3.8 GJ/t P_2O_5 of useful energy as heat. Older technology involved a net input of around 5 GJ/t P_2O_5 as triple superphosphate (Kongshaug pers. Comm.) from mining to granular product. For present purposes, a value of 3 GJ/t P_2O_5 is assumed.

Mining, beneficiation and processing of muriate of potash involves expenditure of 2.5 GJ/t K_2O in most modem plants, 5.9 GJ/t K_2O in older technology. A value of 5 GJ/tK_2O is assumed.

Amounts of energy expended in fertilizers are shown in Table 8, converted from GJ to MJ.

Table 8: Energy equivalents for fertilizers used in crop production

4.3 Agrochemicals (herbicides, fungicides and insecticides)

Typical applications for oilseed rape would be one pre-emergence (metazaclor at 0.5 kg a.i./ha) and one post-emergence (tluazifop-p-butyl at 0.5kg a.i./ha) herbicide application, one flea-beetle spray (cypermethrin at 0.025kg a.i./ha) one fungicide application (flusilazole at 0.25kg a.i./ha) and one insecticide + fungicide application (iprodione + thiophanate-methyl) at 0.5kg a.i./ha). Total assumed application is 1.775kg a.i./ha, equivalent to 5.3 kg product (including packaging). For wheat, typical applications comprise one autumn herbicide (isoproturon at 2.5kg a.i./ha), one spring herbicide (CMPP at 2kg a.i./ha) and two spring fungicide (stobilurin/triazole at 0.5kg a.i./ha each) applications. Total assumed application is 5.5kg a.i./ha, equivalent to 16.5 kg product (including packaging).

An energy equivalent for all agrochemicals of 190 MJ/kg a.i. was assumed (16). Assumptions made elsewhere include 250 MJ/kg a.i. (19) and 101 MJ/kg a.i. (25,26).

4.4 Seed

Typical seed rates of 7 and 185 kg/ha for oilseed rape and wheat respectively are assumed. An energy equivalent of 5 MJ/kg seed is assumed to take into account growth of the seed crop and processing of seed.

4.4 Packaging

It is assumed that fertilizer is delivered to the farm in 500 kg polyethylene/polypropylene IBC bags, agrochemicals in polyethylene containers and seed in paper sacks. Assumed amounts of packaging are 0.0022 kg (4), 0.0030 kg and 0.0050 kg per kg of fertilizer, agrochemical (a.i.) and seed respectively. Values for agrochemicals and seed were arrived at by weighing a sample of relevant containers and bags.

Energy equivalents of 180 MJ/kg are assumed for plastic containers including IBC. (27) and 150 MJ/kg for paper sacks. Calculated energy equivalents for packaging are shown in Table 9 (Energy equivalents of packaging)

4.5 Transport

It is assumed that the farm is 60 miles (approximately 100 km) from the manufacturing or principal distribution centres for fertilizers, agrochemicals and seeds. It is also assumed that the farm is 60 miles from the processing plant to which seed or grain are delivered and, where straw is utilised, 30 miles from the site to which it is delivered. It is further assumed that these materials are delivered on 38 t gross weight (20 t payload) lorries which return empty. In practice, seeds and agrochemicals would be delivered on these lorries to a local merchants store and dispatched from there to the farm on smaller lorries or vans. To a lesser extent, fertilizers also may be delivered to the farm from a merchants store. The energy costs of local deliveries in smaller lorries are difficult to quantify because several deliveries may be made during the year. The amounts of fuel used are likely to be small relative to the uncertainties involved in the main distance assumptions above. However, 5% has been added to the assumed fuel consumption to allow for local deliveries.

It is assumed that rapeseed and grain for processing leave the farm in 38 t gross weight (20 t payload) lorries and that these lorries have no load on the journey from processing plant to the farm. The same size of lorry is assumed for transport of straw but with payload reduced to 15 t.

A fuel consumption of 0.58 / diesel/mile (0.35 / diesel/km) is assumed and an energy equivalent of 43 MJ/1 diesel.

Energy costs for distribution are summarised in Table 10 (Energy costs for distribution to the farm and from farm to processing plant)

4.6 Processing rapeseed and grain into biodiesel and bioethanol

Energy costs for these processes have been quantified at 428 MJ/t biodiesel for rapeseed crushing (10) and 11.0 GJ/t biodiesel and 23.3 GJ/t bioethanol for processing (13). Both estimates are based on natural gas as the primary energy source for processing. For the crop yields and energy contents specified in section 3.2 above, these estimates are equivalent to 17251 MJ/ha and 57620 MJ/ha for oilseed rape and wheat respectively.

Production of biodiesel yields by-product glycerol at 0.04 t/t rapeseed. Other sources of glycerol are soap manufacture (where glycerol is a by-product) and synthesis from petroleum products. The use of glycerol as a fuel for co-firing in biomass plants or as fuel in diesel engines is being investigated in Austria so this by-product has material and probable thermal benefits. For present purposes, a potential energy credit of 35 MJ/kg, equivalent to 5712 MJ/ha at the assumed rapeseed yield of 4.08 t/ha, is given to glycerol. This value is not included in the main calculations but is included in section 5.2 below on the impact of glycerol use as a fuel. Production of bioethanol yields by-product stillage at 0.38 t/t grain (13) that is useful as an animal feed. Stillage has been given an energy value of 2 MJ/kg (13) so for the assumed wheat yield of 8.96 t/ha, there would be an energy credit of 6810 MJ/ha. The net energy cost for processing grain into bioethanol is therefore 50810 MJ/ha. The inclusion of an energy credit depends on the acceptability of stillage as an animal feed where the wheat feedstock is grown on set-aside.

TOP

5. *Energy Balance*

5.1 Basic calculations

Energy balances for different situations are summarised in Table 11.

5.2 Impact on the energy balance if glycerol is used as a fuel

The energy balance for biodiesel is significantly improved if glycerol is used as a fuel. With a value of 5712 MJ/ha (see section 4.6 above), glycerol use would reduce the total energy costs for biodiesel by the same amount and increase the energy balance from 25157 to 30869 MJ/ha where straw is ploughed in and from 84500 to 90212 MJ/ha where straw is utilised. The energy costs per GJ of biodiesel would be reduced from 561 to 456 MJ where straw is ploughed in and from 573 to 468 MJ where straw is utilised.

TOP

6. *Emissions and apparent recovery of fertilizer N*

6.1 Emissions in fertilizer manufacture and agriculture

Sections 6.1 and 6.2 are intended to act as sources of relevant data to be used in conjunction with those from other sources in analyses outside the scope of this report. Emissions may be to atmosphere (mainly NH_3, NO_x and CO_2) and to water (N and P compounds) and occur during fertilizer manufacture, from the soil after fertilizer application and during vehicle operation. There are emissions to atmosphere and to water from all soils, whether or not fertilizers are applied. Figures given here therefore refer to additional emissions that can be associated with fertilizer use.

Data for emissions from a modern fertilizer-manufacturing complex, established by EFMA (12) are summarised in Table 12 (Emissions from a modem fertilizer manufacturing plant. (Figures in parenthesis are mean values)).

Technology now being introduced will reduce N_2O emissions from nitric acid plants by some 80%.

Taking the mean values from Table 12 and the assumed rates of fertilizer application, emissions can be quantified on the basis of land area for oilseed rape and wheat (Table 13).

The main emissions following fertilizer application are NH_3 and N_2O to air and nitrate-N to water. NH_3 emissions following fertilizer application have been summarised by ECOTOC (11). Under UK climatic conditions, around 0.02 kg NH_3 is lost for every kg N applied as ammonium nitrate.

Published data on emission of N_2O following fertilizer application have been summarised by Granli and Bockman (14). The range for emission is 0.4 -1.7 kgN_2O for every 100 kg N applied as ammonium nitrate. A value of 1.0 kg N_2O/100 kg N is assumed

N may be lost to water by leaching to an extent that will depend on soil and climatic conditions and by the efficiency of fertilizer use. Where N is applied after the main period of leaching (that is after mid-February in the UK), and at a rate not exceeding the economic optimum, the risk of leaching will be low (15, 20). The proportion of N applied as ammonium nitrate that is lost by leaching is assumed to be 0.01.

CO_2 and NOx are emitted during vehicle operation at typical rates of 2.6 kg CO_2 and 40g NO_x/l diesel respectively (12). These rates of emission are assumed for both farm tractors and lorries. For oilseed rape, total diesel consumption is 162 l/ha where straw is ploughed in and 210 l/ha where straw is utilised. Corresponding values for wheat are 167 l/ha and 222 l/ha. Total emissions of CO_2 and of NO_X are dominated by those arising from vehicle use. There would be therefore a significant beneficial effect on emissions, particularly of CO_2, if biodiesel were used for transport and farming operations. In this case, CO_2 released during vehicle use would be recently fixed and so would not represent a net addition to the atmosphere.

Emissions during fertilizer manufacture and following application are summarised in Table 13. The values shown should be regarded as typical and subject to considerable variation due to differences among fertilizer plants in level of technology and among crops in soil and climatic conditions. The efficiencies of both fertilizer manufacture and crop growth are also strongly influenced by management.

Table 13 Emissions during fertilizer manufacture, following application and during vehicle operation expressed on a unit area basis.

6.2. Apparent recovery of applied N in the crops

The amounts of N removed from the field in rapeseed and grain are shown in Table 2 and Table 4 and in Fig 1 and Fig 2. Relationships between the amounts removed and those applied are curvilinear and are described by equations 3 and 4:

$$Nr = 54.69 + 0.467N - 0.000804N^2 \qquad (3)$$

$$Ng = 64.99 + '0.624N - 0.00083JN^2 \qquad (4)$$

where Nr is N offtake in rapeseed kgN/ha

Ng is N offtake in wheat grain kgN/ha

N is rate of applied N kgN/ha

The apparent recovery of N in rapeseed or grain at any rate of applied N can be calculated by differentiating equations 3 and 4. Apparent recovery is defined by:

$N_{ar} = (N_y - N_{y0})/N_x$ (5)

Where N_{ar} is apparent N recovery at N rate N_x expressed as a proportion

N_y is N offtake at N rate N_x kgN/ha

N_{y0} is N offtake where no N is applied kgN/ha

At the assumed rates of fertilizer N application (180 kgN/ha and 195 kgN/ha for oilseed rape and wheat respectively), apparent recoveries of applied N are 0.32 and 0.46 for oil seed rape and wheat respectively. Thus, for oilseed rape, an amount of N equivalent to 68% of that applied is not accounted for in the grain. The corresponding figure for wheat is 54%. This unaccounted for N occurs in the straw and as an accumulation in soil organic matter. Only a small proportion, equivalent to around 1% of that applied will be lost to air or water in the year of application.

TOP

7. *Bases of calculation*

Figures in sections 1 to 6 above, calculated on a unit area basis, are summarised below and shown on different bases in Tables 14 (Summary of energy values and costs) and in Table 15 (Summary of emissions).

Table 14 shows that, if only the energy values of the biodiesel or bioethanol are taken into account (ignoring the value of straw and cake), all systems considered provide a positive energy balance -the ratio of energy cost to energy value of the biodiesel or bioethanol is less than 1. This is most marked for biodiesel where less than 0.6 GJ is employed in producing 1.0 GJ of biodiesel.

TOP

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TOP

9: *Acknowledgements*

For the help given in the preparation of this document by

- John Deere Ltd
- Hydro Agri U.K. Ltd
- Fertilizer Manufacturers Association

TOP

Table 1 Seed yield of oilseed rape at different rates of applied nitrogen (t/ha)

Rate of nitrogen application as ammonium nitrate (kgN/ha)									
Trial	Year	0	80	120	160	200	240	280	SE/plot
1	1994	1.51	3.29	4.08	4.48	4.23	4.17	4.74	0.302
2	1994	3.40	4.44	4.85	5.36	5.16	4.53	5.91	0.478
3	1994	2.34	3.73	3.62	3.85	4.11	4.26	3.58	0.305
4	1995	3.02	3.86	3.94	5.08	5.09	5.11	4.80	0.510
5	1995	2.00	3.11	3.68	3.75	4.35	4.58	4.45	0.271
6	1995	1.63	2.70	3.40	3.64	4.16	4.02	4.21	0.200
7	1996	1.66	2.90	2.92	2.71	3.10	3.21	2.87	0.213
8	1996	3.80	4.51	4.36	3.97	4.81	4.28	4.06	0.450
9	1966	3.04	4.44	4.04	3.95	3.69	4.07	3.18	0.554

9	1966	3.04	4.44	4.04	3.95	3.69	4.07	3.18	0.554
10	1997	2.43	3.41	3.47	3.55	3.36	3.21	3.17	0.327
11	1997	2.72	3.89	4.30	4.16	4.44	4.31	4.58	0.479
12	1997	1.52	2.76	3.57	3.85	3.86	4.18	4.43	0.268
13	1998	1.51	2.94	3.51	3.65	4.12	3.82	4.31	0.320
14	1998	1.78	3.31	3.41	3.77	4.03	4.09	2.80	0.329
15	1998	1.82	3.12	3.29	3.47	3.75	3.92	4.03	0.206
Mean		2.28	3.49	3.76	3.95	4.15	4.12	4.08	0.370

Table 2 Offtake of nitrogen in oilseed rape at different rates of applied nitrogen (kgN/ha)

Rate of nitrogen application as ammonium nitrate (kg/ha)									
Trial	Year	0	80	120	160	200	240	280	SE/plot
1	1994	32.3	70.5	96.5	120.7	117.7	126.2	141.4	9.50
2	1994	89.0	114.9	126.8	141.4	147.4	133.6	174.8	14.06
3	1994	62.0	102.1	100.2	111.2	118.6	128.4	109.7	10.15

4	1995	64.4	87.3	95.4	133.2	139.3	146.9	140.5	14.35
5	1995	43.6	69.0	86.5	97.0	113.9	123.6	124.3	8.72
6	1995	37.9	63.7	84.8	94.7	111.6	113.3	124.4	5.64
7	1996	43.9	90.6	94.2	86.2	111.3	109.4	100.6	8.16
8	1996	90.9	121.8	122.7	115.3	144.6	134.2	127.6	14.34
9	1996	73.6	118.1	105.0	112.6	105.8	118.4	91.9	14.49
10	1997	60.4	85.7	91.5	97.2	89.0	90.4	90.2	9.72
11	1997	64.0	107.0	122.0	127.3	137.9	141.7	146.9	14.81
12	1997	38.1	67.3	96.7	100.2	109.5	124.9	132.0	9.39
13	1998	35.7	69.2	84.0	92.6	105.4	105.9	122.9	8.77
14	1998	44.0	73.9	80.2	96.4	106.4	111.2	80.5	10.74
15	1998	41.3	77.3	81.9	87.5	98.0	106.6	112.2	6.35
Mean		54.7	87.9	97.8	107.6	117.1	121.0	121.3	11.02

Table 3 Grain yield of winter wheat at different rates of applied nitrogen (t/ha)

Rate of nitrogen application as ammonium nitrate (kgN/ha)

Trial	Year	0	80	120	160	200	240	280	SE/plot
1	1994	4.25	7.23	8.13	8.43	8.47	8.67	8.52	0.301
2	1994	5.07	7.20	8.00	8.50	8.72	8.84	8.76	0.492
3	1994	4.15	6.92	7.90	8.36	8.88	9.03	9.55	0.399
4	1995	2.90	5.19	6.23	6.34	6.85	6.64	6.57	0.411
5	1995	3.51	6.58	7.59	8.16	8.85	9.26	8.92	0.351
6	1995	4.61	7.27	7.71	8.49	8.25	8.46	8.93	0.286
7	1996	3.90	7.28	8.60	8.96	9.56	9.69	9.39	0.430
8	1996	6.67	7.99	9.23	9.91	10.08	10.36	9.98	0.861
9	1996	9.24	10.97	11.25	11.18	11.46	11.73	10.79	0.505
10	1997	3.67	6.01	6.96	7.28	7.54	7.50	7.58	0.244
11	1997	4.83	6.67	7.07	8.61	7.04	7.05	7.57	1.131
12	1997	6.52	8.10	8.93	9.67	9.50	10.10	9.70	0.373
13	1998	5.74	6.89	8.08	8.22	8.58	9.11	9.36	0.804
14	1998	5.15	8.04	9.05	9.54	10.65	10.37	10.11	0.456
15	1998	4.74	7.85	7.80	8.34	8.96	8.79	9.07	0.465
Mean		5.00	7.35	8.17	8.66	8.89	9.04	8.99	0.550

Table 4 Offtake of nitrogen in wheat grain at different rates of applied nitrogen (kgN/ha)

Rate of nitrogen application as ammonium nitrate (kgN/ha)									
Trial	Year	0	80	120	160	200	240	280	SE/plot
1	1994	55.5	96.2	111.6	131.9	140.9	161.7	153.6	6.44
2	1994	63.9	94.5	130.8	134.4	147.5	163.8	164.8	11.92
3	1994	58.8	101.5	123.1	148.7	170.5	177.7	194.5	8.07
4	1995	37.4	73.2	103.2	118.2	141.7	144.1	150.0	10.40
5	1995	45.7	82.2	109.5	128.2	154.3	173.2	172.4	9.44
6	1995	62.9	115.8	133.8	151.2	169.5	188.2	183.1	11.29
7	1996	43.1	83.2	109.7	127.3	145.5	145.4	145.7	6.26
8	1996	84.1	105.5	139.3	160.5	164.9	176.7	175.0	14.99
9	1996	113.6	148.8	173.1	183.5	191.9	205.8	187.2	10.48
10	1997	83.2	114.3	118.7	154.6	127.3	141.5	158.0	12.22
11	1997	58.9	105.6	138.1	159.1	146.9	151.8	158.0	18.84
12	1997	91.9	124.1	138.5	153.7	162.0	188.4	174.4	10.90
13	1998	77.3	82.5	117.6	116.0	139.9	154.5	167.5	13.01
14	1998	62.8	109.5	134.3	157.7	184.2	190.3	199.3	10.24
15	1998	66.5	131.1	137.2	57.1	175.4	182.3	188.8	13.68

15	1998	66.5	131.1	137.2	57.1	175.4	182.3	188.8	13.68
Mean		67.1	104.5	127.8	145.5	157.5	169.7	171.5	11.64

Table 5: **Energy values of oilseed rape and wheat crops**

	Oilseed rape	Wheat
Seed/grain yield (t/ha)	4.08	8.96
Straw yield (t/ha)	4.00	6.50
By-product cake or bran (t/ha)	2.37	0.03
Biodiesel/ethanol yield (t/ha)	1.51	2.47
Energy value of yield (MJ/ha)	54346	74189
Energy value of straw (MJ/ha)	60000	97500
Energy value of by-product (MJ/ha)	1316	
Total energy value straw ploughed in (MJ/ha)	55662	74189
Total energy value straw utilised in (MJ/ha)	115662	171689

Table 6: **Agricultural fuel consumption assumptions**

Operations	Work rate ha/hour	Fuel use (l/ha harvested)

Sub-soil tramlines	10	2.5
Plough 75kw (230mm heavy soil)	1	24
Mulch tiller	6	8.5
Double deep disc	1	24.5
Power harrow/combination drill	0.75	32
Drill	12	10
Roll	2.5	6.5
Fertilizer application	9	2.2
Spray	9	2.2
Swath	10	10
Combine	3.25	15.5
Grain/seed cart 2 tractors	3.25	4.5
Straw bale	3	6
Straw cart from field 2 tractors	3	5

Table 7: **Fuel energy consumed in farming operations**

Operations	Oilseed fuel rape fuel used (l/ha)	Wheat fuel used (l/ha)	Oilseed rapefuel energy (MJ/ha)	Wheat fuel energy (MJ/ha)

Sub-soil tramlines	2.5		107	
Plough 75kw 230mm heavy soil		24		1032
Double deep disc	24.5		1053	
Cultivation (x2)		24		1032
Power harrow/combination drill	32		1376	
Drill		10	430	
Roll	6.5	6.5	280	280
Fertilizer application (x3)	6.6	6.6	284	284
Spraying (x5 for rape, x4 for wheat)	11	8.8	473	378
Dessicant	2.2		95	
Combining	15.5	15.5	666	666
Grain/seed carting 2 tractors	4.5	4.5	194	194
Straw baling	3	6	129	258
Straw carting 2 tractors	3	5	172	215
Stubble mow	4		129	

Total (straw ploughed in	109	100	4687	4300
Total (straw utilised)	115	111	4945	4773

Table 8: **Energy equivalents for fertilizers used in crop production**

Nutrient	Oilseed rape kq/ha	Wheat straw ploughed in kq/ha	Wheat straw utilised in kq/ha	Oilseed rape MJ/ha	Wheat straw ploughed in MJ/ha	Wheat straw MJ/ha
N	180	195	195	6840	7410	7410
P205	50	60	70	150	180	210
K20	40	45	90	200	225	450
Total				7190	7815	8070

These amounts of nutrients are equivalent to 697 (oilseed rape), 771 (wheat, straw ploughed in) and 867 (wheat, straw utilised) kg product/ha if the sources are ammonium nitrate, triple superphosphate and muriate of potash.

Table 9: **Energy equivalents of packaging**

	Oilseed rape (straw ploughed in MJ/ha	Oilseed rape (strawutilised MJ/ha	Wheat straw ploughed in MJ/ha	Wheat straw utilised MJ/ha
Fertilizers	276	276	305	343

Agrochemicals	1	1	3	3
Seed	5	5	139	139
Total	282	282	447	485

Table 10: **Energy costs for distribution to the farm and from farm to processing plant**

	Oilseed rape kg/ha	Wheat straw ploughed in kg/ha	Wheat straw utilised in kg/ha	Oilseed rape MJ/ha	Wheat straw ploughed in MJ/ha	Wheat straw utilised MJ/ha
Fertilizer	697	771	867	110	122	137
Agrochemicals	5.3	16.5	16.5	1	3	3
Seeds	7	185	185	1	29	20
Seed/grain	4080	8960	8960	611	1341	1341
Straw	4000	6500	6500	399	0	648
Total straw ploughed in				723	1495	
Total straw utilised				1122		2149

Table 11 **Energy balance for biodiesel from oilseed rape and bioethanol from wheat**

Energy yield (+)or cost(-)	**Oilseed rape, straw ploughed in MJ/ha**	**Oilseed rape, straw utilised MJ/ha**	**Wheat, straw ploughed in MJ/ha**	**Wheat, straw utilised MJ/ha**
Biodiesel/ bioethanol	**+54346**	**+54346**	**+74189**	**+74189**
Cake/bran	**+1316**	**+1316**	**+0**	**+0**
Straw	**+0**	**+60000**	**+0**	**+97500**
Total	**55662**	**+115662**	**+74189**	**+171689**
Agricultural fuel	**-4687**	**-4945**	**-4300**	**-4773**
Fertilizers	**-7190**	**-7190**	**-7815**	**-8070**
Agrochemicals	**-337**	**-337**	**-1045**	**-1045**
Seed	**-35**	**-35**	**-925**	**-925**
Packaging	**-282**	**-282**	**-447**	**-485**
Transport	**-723**	**-1122**	**-1495**	**-2149**
Processing	**-17251**	**-17251**	**-50810**	**-50810**
Total	**-30505**	**-31162**	**-66837**	**-68257**
Balance	**+25157**	**+84500**	**+7352**	**+103432**

The total estimated energy cost for growing wheat, 16027 MJ/ha where straw is ploughed in, is similar to the figure of 15510 MJ/ha calculated independently in Germany (17).

	Ammonia plant kg/tN	Nitric acid plant kg/tN	Finished NPK plant kg/tN
To air			
NH3	0	0	0.7-25 (1.5)
NOx	0.1-2.3 (0.7)	**0.1-2.2 (0.3)**	
N20		27	
CO2	450- 2080 (1140)		
Dust			0.5
To water			
N	0.04-0.8 (0.2)		0.3-2.7 (1.8)
P			0.1-60 (0.6) kgP/tP

Table 13 **Emissions during fertilizer manufacture, following application and during vehicle operation expressed on a unit area basis.**

	Oilseed rape (straw ploughed in) kg/ha	Oilseed rape (straw utilised) kg/ha	Wheat (straw ploughed in) kg/ha	Wheat (straw utilised) kg/ha
To air				
NH_3	3.87	3.87	4.19	4.19

NO_x	6.66	8.58	6.88	9.08
N_2O	6.66	6.66	7.41	7.41
CO_2	626	751	656	799
To water				
N compounds during manufacture	0.36	0.36	0.39	0.39
Nitrate N after use	1.8	1.8	2.0	2.0
P compounds during manufacture	0.02	0.02	0.03	0.03

Table 14 **Summary of energy values and costs**

	Oi1seed rape. straw ploughed in	Oi1seed rape. straw utilised	Wheat. straw ploughed in	Wheat. straw utilised
Per hectare				
Seed/grain yield (t)	4.08	4.08	8.96	8.96
Biodiesel/bioethanol yield (t)	1.51	1.51	2.47	3.47

Energy value of biodiesel/bioethanol (MJ)	54346	54346	74189	74189
Energy va1ue of straw (MJ)	0	60000	0	97500
Energy value of cake (MJ)	1316	1316	0	0
Energy cost (MJ)	30505	31162	66837	68257
Energy balance (MJ)	+25157	+84500	+7352	+103432
Per tonne seed/grain				
Biodiesel/bioethanol yield (kg)	370	370	276	276
Energy value of biodiesel/bioethanol (MJ)	13320	13320	8280	8280
Energy va1ue of straw (MJ)	0	14706	0	10882
Energy value of cake (MJ)	323	323	0	0
Energy cost (MJ)	7477	7638	7459	7618
Energy ba1ance (MJ)	+6166	+20711	+821	+ 11544
Per GJ biodiesel/bioethanol				
Energy cost (MJ)	561	573	901	920
Per GJ biodiesel/bioethanol/straw/cake				
Energy cost (MJ)		269		398

Table 15 **Summary of emissions**

	Oi1seed rape	Oi1seed rape	Wheat straw	Wheat rape
Per hectare				
To air				
NHJ (kg)	3.87	3.87	4.19	4.19
NOx (kg)	6.66	8.58	6.88	9.08
N20 (kg)	6.66	6.66	7.41	7.41
CO2 (kg)	626	751	656	799
To water				
N compounds (kg)	2.16	2.16	2.39	3.39
P compounds (kg)	0.02	0.02	0.03	0.03
Per tonne seed/grain				
NHJ (kg)	0.95	0.95	0.47	0.47
NOx (kq)	1.63	2.10	0.77	1.01
N20 (kq)	1.63	1.63	0.83	0.83

N20 (kq)	1.63	1.63	0.83	0.83
CO2 (kg)	153	184	73	89
To water				
N compounds (kg N)	0.52	0.52	0.27	0.27
P compounds (kg P)	0.005	0.005	0.003	0.003
Per GJ biodiesel/bioethanol				
To air				
NHJ (kg)	0.071	0.071	0.056	0.056
NOx (kg)	0.123	0.158	0.093	0.122
N20 (kg)	0.123	0.123	0.100	0.100
CO2 (kg)	11.5	13.8	8.8	10.8
To water				
N compounds (kg)	0.040	0.040	0.032	0.032
P compounds (kg)	0.0004	0.0004	0.0004	0.0004

Fig 1

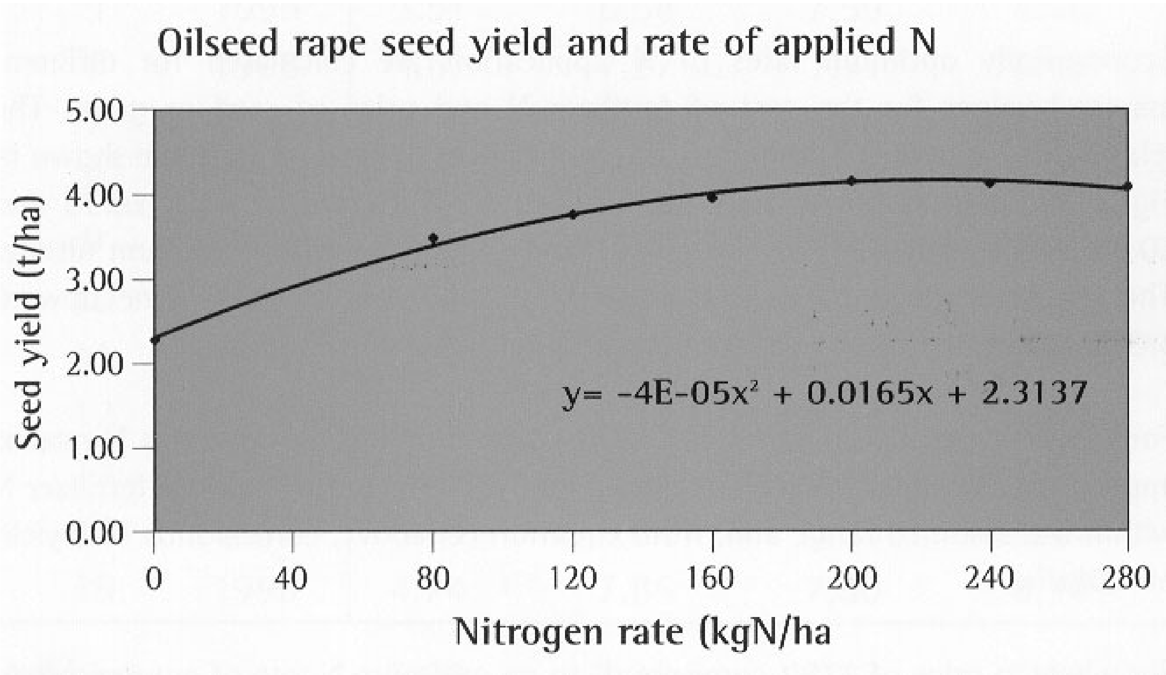

Oilseed rape seed yield and rate of applied N
Seed yield (t/ha)
5.00
4.00
3.00
2.00
1.00
0.00
0
40
80
120
160
200
240
280
Nitrogen rate (kgN/ha
y= -4E-05x² + 0.0165x + 2.3137

Fig 2

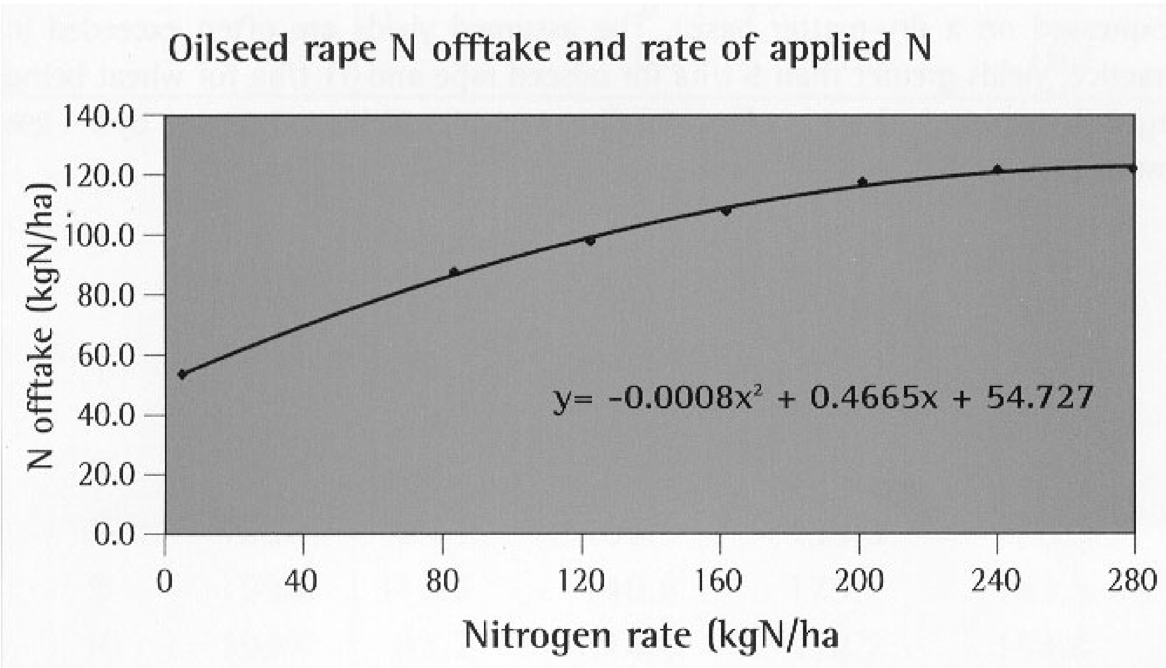

Oilseed rape N offtake and rate of applied N
N offtake (kgN/ha)
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
40
80
120
160
200
240
280
Nitrogen rate (kgN/ha
y= -0.0008x² + 0.4665x + 54.727

Fig 3

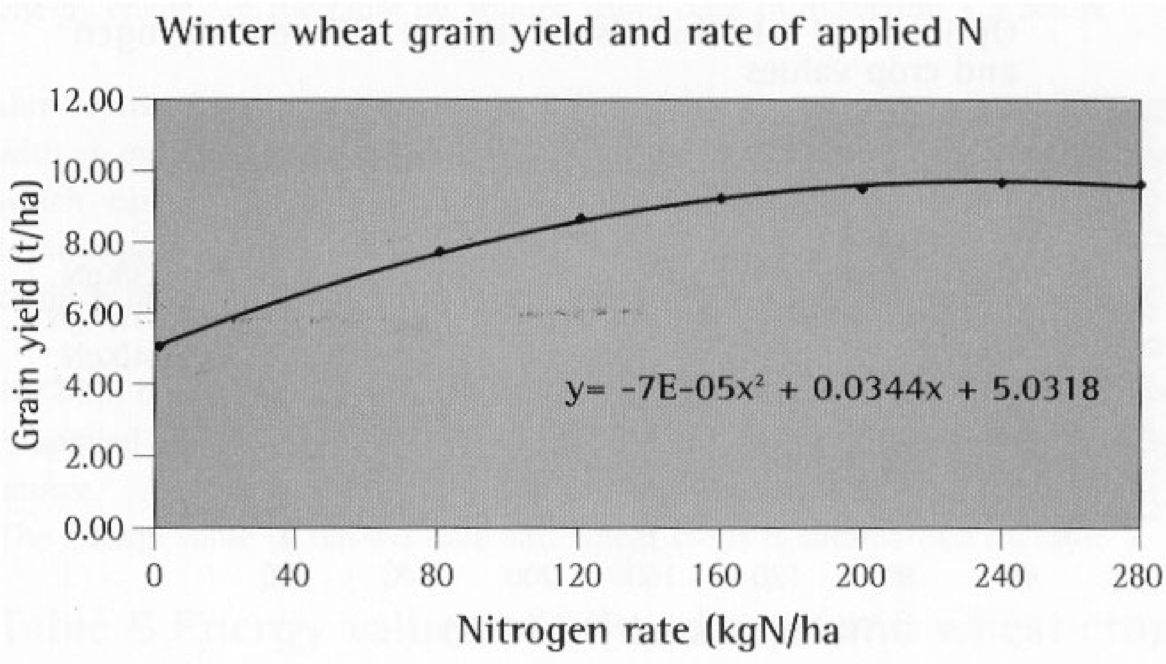

Winter wheat grain yield and rate of applied N
Grain yield (t/ha)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
40
80
120
160
200
240
280
Nitrogen rate (kgN/ha
y= -7E-05x² + 0.0344x + 5.0318

Fig 4

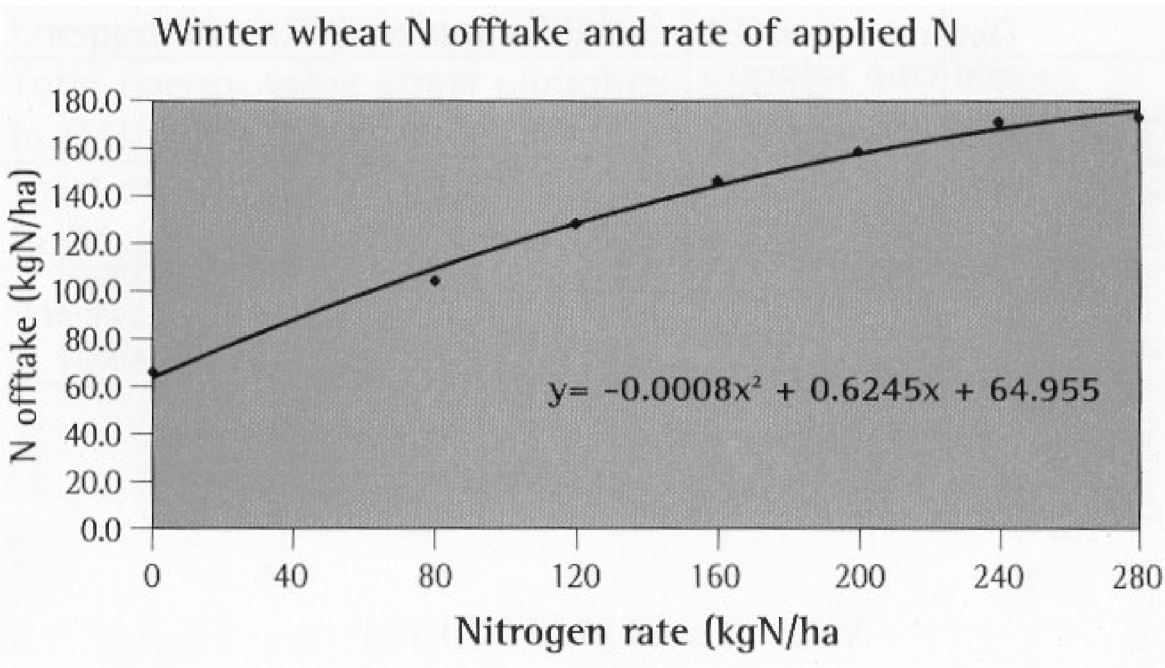

Winter wheat N offtake and rate of applied N
N offtake (kgN/ha)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
40
80
120
160
200
240
280
Nitrogen rate (kgN/ha
y= -0.0008x² + 0.6245x + 64.955

Fig 5

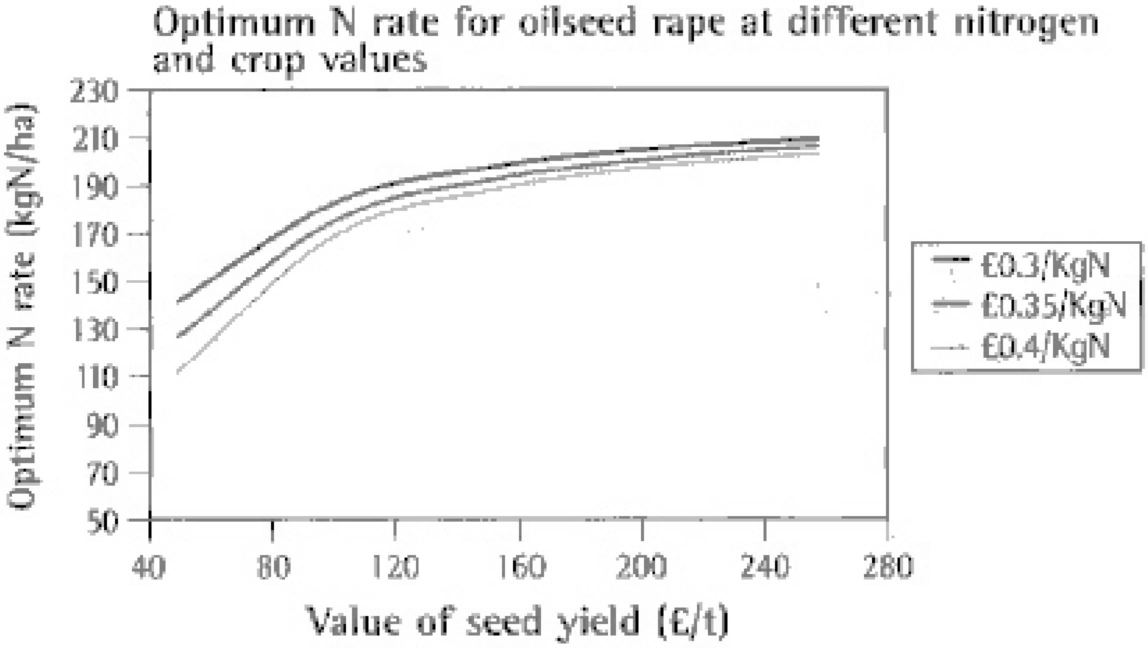
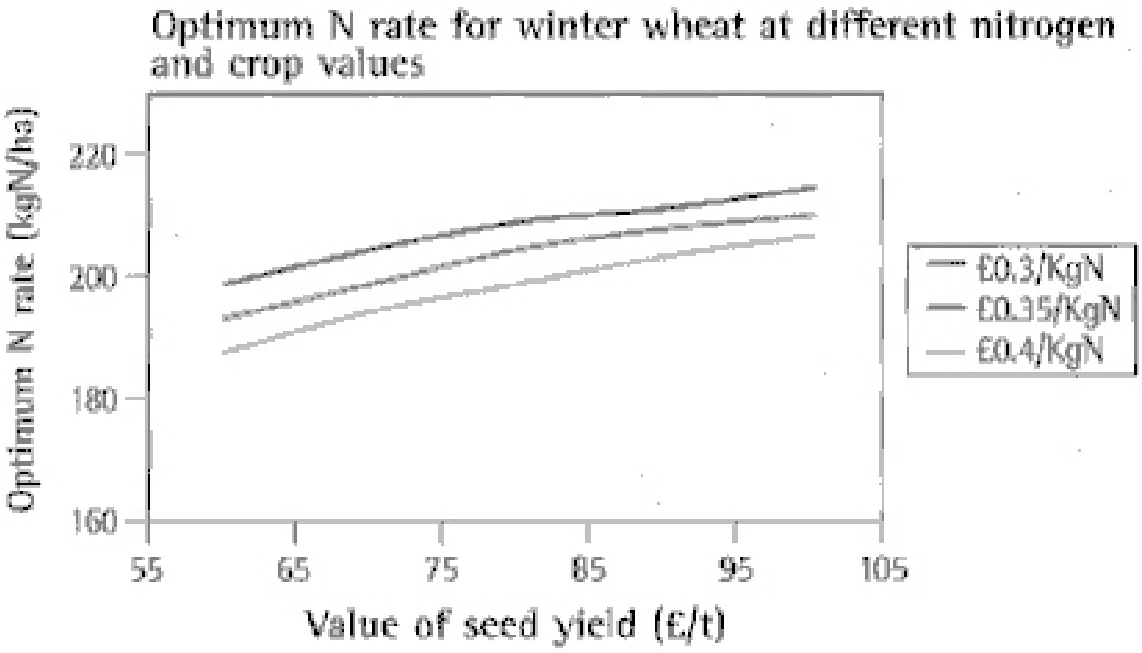

Optimum N rate for oilseed rape at different nitrogen and crop values
Optimum N rate (kgN/ha)
230
210
190
170
150
130
110
90
70
50
40
80
120
160
200
240
280
Value of seed yield (£/t)
£0.3/KgN
£0.35/KgN
£0.4/KgN

Fig 6


Optimum N rate for winter wheat at different nitrogen and crop values
Optimum N rate (kgN/ha)
220
200
180
160
55
65
75
85
95
105
Value of seed yield (£/t)
£0.3/KgN
£0.35/KgN
£0.4/KgN