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CANOPY MANAGEMENT IN WINTER OILSEED RAPE

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CANOPY MANAGEMENT IN WINTER OILSEED RAPE

by

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Contents

Appendix I: Effect of canopy size and architecture on yield of oilseed rape

Appendix II: Effects of seed rate, sowing date and defoliation on yield of oilseed rape

Appendix III: Effects of N fertilisation on canopy size and yield of oilseed rape

Appendix IV: Effects of pest and disease management strategy on canopies of different size on yield of oilseed rape

Abstract

Many commercial oilseed rape crops, sown early, at high seed rate and with plentiful nitrogen fertilisation, have canopies that are too large. A series of experiments was conducted where canopy size was varied by sowing date (early or late September), seed rate (120 or 60 seeds m^{-2}), nitrogen fertiliser (0 – 300 kg ha^{-1} N) and mowing. The dry matter and green area indices of leaf, stem and pod throughout development were determined by growth analysis and yield and yield components were measured. In 1998 and 1999, the potential for reducing pesticide and insecticide inputs to small canopies was assessed, with detailed records of pest and disease incidence and yield.

It was shown that no yield benefit occurred above a critical pre-flowering crop size (LAI of 1.75 or GAI of 3). A strong linear relationship between pod density and seed number per pod explained the capacity of sparse crops (with fewer pods but more seeds per pod) to yield as well as denser canopies (with fewer seeds per pod), due to compensatory growth. Yield was limited in very sparse crops by too few (<4,000 m^{-2}) pods and in very dense crops by too few (<10 pod^{-1}) seeds per pod. Analysis of canopy management by seed rate and sowing date, showed that similar canopy sizes and yields could be achieved from 60 and 120 seeds m^{-2} since plants grown at the lower seed rates produced more green area per pod and more pods per plant than those in the higher seed rate.

Similar yields were achieved by early (end August) and late (end September) sowings if spring conditions were favourable for growth, although in some years the yield of later-sown crops was slightly lower. Mowing did not produce as large a yield benefit as in previous work as the crops to be mown were not too large to start with. Study of the effect of nitrogen supply indicated that excess leaf area and high pod numbers were produced with plentiful N availability, explaining the deleterious effect of over-fertilisation with N. The relationship between yield and soil nitrogen supply (SNS) was a linear plus exponential curve, with an optimum of about 125 kg N per ha. In some years, spring soil mineral N (SMN) was sufficient to supply all of this requirement and N application consequently caused large losses in margin.

Comparison of N application strategies (zero N, book recommendation of 230 kg N ha^{-1} and N fertiliser applied to boost SMN to the required SNS) showed reductions of £37 and £59 ha^{-1} in average margin respectively compared to the application taking SMN into account. Not using fungicide caused a yield loss of up to 1.2 t ha^{-1} in 1998, but no significant loss in 1999, as disease levels were low. Not using insecticide caused no significant yield penalty in either year. Assessment of the margin of yield value over chemical and application costs showed that, on average, double prophylactic spraying was the least profitable strategy, and zero fungicide application gave an acceptable margin. There were therefore indications that reduced inputs, especially to smaller (late sown, low seed rate) crops were possible. Thus the potential benefits of 'canopy management' have been demonstrated and the agronomic means to achieve them identified.

Summary

1. Introduction

Current agronomic practices tend to produce crops that are significantly larger than the optimum size, through early sowing at high seed rates with plentiful nitrogen fertilisation. These crops look well and lush in the spring and may have advantages for improved competition against weeds and resilience to pigeon damage. However, production of such crops reduces the profitability of rape due to the extra costs of unnecessary inputs, which may additionally cause yield reduction. Many commercial crops may develop well over 10,000 pods m^{-2}. To achieve a 4.5 t ha^{-1} yield of oilseed rape, 450 g of seed must be produced per square metre. Assuming an average seed weight of 4.5 mg (at 9% moisture), 100, 000 seeds m^{-2} must be produced. If the average number of seeds per pod is 20, this yield can be achieved from 5,000 pods m^{-2}. If seed number is reduced to 10 per pod (due to shading and abortion in dense canopies) then 10,000 pods m^{-2} are required to generate a 4.5 t ha^{-1} yield, with the extra pod and stem biomass reducing the harvest index considerably, and requiring extra inputs. If oilseed rape is to remain a profitable component of the rotation, it is clearly desirable to produce the optimum yield from smaller, more effective canopies (with larger harvest indices), requiring fewer resources (reduction of variable costs of nutrition and crop protection).. This is the ‘Canopy Management’ approach being investigated in this study.

2. Objectives and benefits

The first objective of the research was to test the underlying principle that yields of oilseed rape could be explained in terms of the influences of season, site and crop management on the size and architecture of the canopy and how this controls light capture and yield formation. The hypothesis that seed yields of oilseed rape can be explained in terms of canopy structure, light distribution and pod and seed retention was tested at ADAS Rosemaund and Sutton Bonington in years 1, 2 & 3 (Appendix I and II). The hypothesis that fertiliser nitrogen (N) can be used to regulate canopy size and architecture to improve light distribution and pod and seed retention was tested at Sutton Bonington in years 1, 2 & 3 (Appendix III). The second objective was to investigate the implications of producing yields from smaller canopies on the costs of production. The hypothesis that canopy size and architecture would affect the pressure from pests and diseases thus have a bearing on control measures was tested at ADAS Rosemaund in years 3 & 4 (Appendix IV).

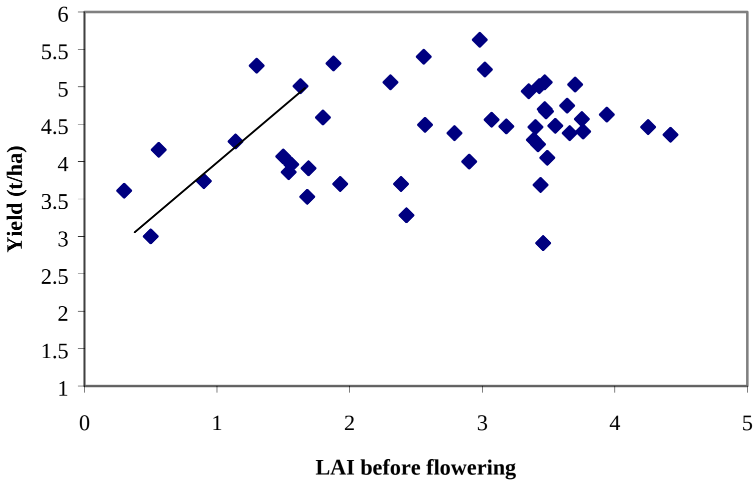
3. Materials and Methods

At ADAS Rosemaund crops were sown at an early (normal) sowing date (last week of August/first week of September) and a late sowing date at the end of September at two seed rates, a high/conventional rate of 120 seeds m^{-2} (about 5.4 kg ha^{-1}) and a halved rate of 60 seeds m^{-2}/2.7 kg ha^{-1}. In 1996 and 1997, the effects of defoliation with an Allen scythe in February were studied. In 1998 and 1999, the effects of different fungicide and pesticide management strategies on yield and margin were studied. With prophylactic control of either fungi or insects, the effects of prophylactic spraying, managed spraying or no application of insecticide or fungicide was studied, respectively. At Sutton Bonington, plots were marked out in farm-drilled crops in the spring. Soil mineral nitrogen levels (kg ha^{-1}) were determined by ADAS laboratories in February from 90 cm cores taken from at least 10 locations in a W pattern across the crop. Nitrogen fertiliser (ammonium nitrate prills) was then applied in various splits in March and April to study the yield response. All experiments were split plot plus factorial or fully randomised designs with four replicate blocks. The three most representative blocks were chosen for detailed growth analysis in the spring, which was carried out in a sub-set of the treatments at each site. At regular intervals throughout crop development from early spring, all the above ground material from one metre squared quadrats was collected from each replicate. In the laboratory, the plant number was counted and a 20% subsample was taken for determination of fresh and dry mass (oven drying for 48 h at 85°C). A second subsample was taken and the fresh and dry mass of stems and leaves, and flowers, buds and pods when appropriate, was recorded in separate fractions. The green area of stems, leaves and pods was recorded separately for each fraction with Licor or Delta T electronic leaf area meters. For stems and pods the projected area was multiplied by $\pi/2$ (1.57) to give the green area index (GAI) of a half cylinder. The numbers of flowers, buds and pods in subsamples were counted by hand and the relevant numbers and dry matters per ha were calculated with the relevant subsample dry/fresh matter ratios. At particular stages of development, light interception readings were taken with Delta T ceptometers. Simultaneous reading using two ceptometers were taken, to give incident radiation and radiation transmitted to various levels of the crop canopy. Plots were combined directly or after spraying with the desiccant diquat at the end of July or beginning of August with a Sampo plot combine harvester. Harvested yields and plot lengths were recorded to allow calculation of yield (t ha^{-1}) after final seed cleaning. Automatic seed counters were used to count 1000 seeds and record the thousand seed weight. Replicate samples were oven dried (48 h, 85°C) and the dry weight was determined. Yields were expressed on a 91% dry matter basis. All statistical analyses were carried out using Genstat 5 for Windows software. All quoted LSDs and SEDs are at the 5% level of significance unless otherwise stated.

4. Results and Discussion

The results showed that a leaf area index (LAI) before flowering above a value of about 1.75 was needed for achievement of optimum yield (Figure 4). In terms of total crop green area index (data not shown), the critical value was about 3-4. With LAI < 1.75 (GAI < 3), yield could be limited (e.g. some late-sown crops).

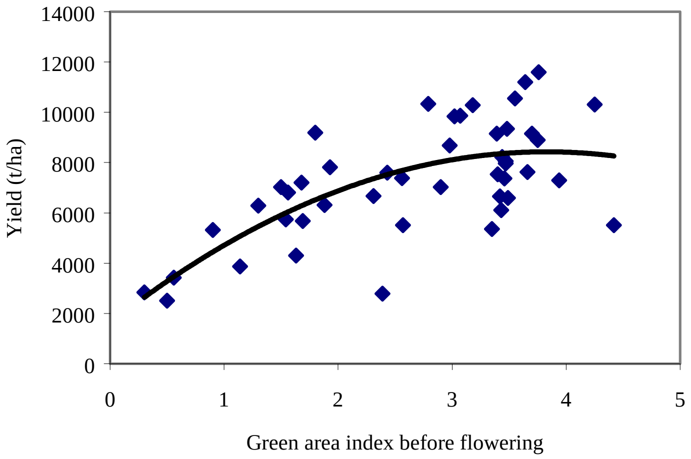
Figure 4: Effect of leaf area index (LAI) before flowering on yield



This result correlated with previous work of Mendham *et al.* (1981) and Habekotté (1997). However, very few crops had LAIs below the critical value before flowering. No benefit of crops with LAIs prior to flowering exceeding 1.75 was identified. Greater pre-flowering LAI caused production of more pods after flowering and there was a trend for reduction in pod number and thus yield with high pre-flowering LAI (Figure 5).

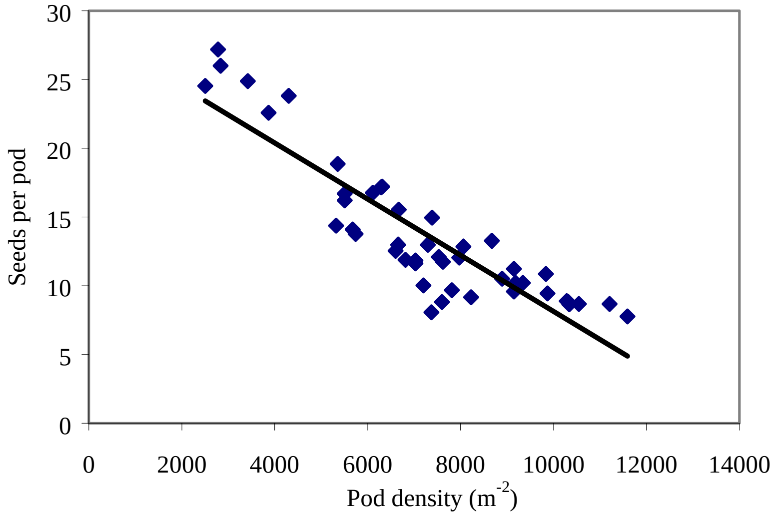
Large canopies produced more flowers and potential pod sites, with poorer light penetration. The fraction of fertile pods produced from these potential sites was often smaller (as low as 15%) in large canopies than in sparser canopies (over 60%), such that similar pod densities were derived from vegetative canopies of varying size, although there would appear to be an interaction with radiation levels at flowering.

Figure 5: Effect of leaf area index before flowering on fertile pod density



The reduction in seed numbers per pod caused by increasing numbers of pods (high pod density) was confirmed, with a very strong linear relationship identified (Figure 6). Due to the ability of sparser canopies to produce nearly as many pods as thick canopies and the ability of higher seed numbers per pod to compensate for lower pod numbers in sparse canopies, production of smaller canopies did not cause a yield penalty. However, the possibility of yield loss from both very small canopies (too few pods, < 4,000 m^{-2}) and too large canopies (too few seeds per pod, < 10 pod^{-1}) was identified.

Figure 6: Effect of pod density on seed number per pod



Alteration of canopy structure by reduction of seed rate from 5.4 kg ha^{-1} (120 seeds m^{-2}) to 2.7 kg ha^{-1} (60 seeds m^{-2}) caused no reduction in yield in three out of four cases studied (non-significant numerical increases were recorded). Growth analysis showed that this was due to the ability of sparser populations to produce more green area per plant and more pods per plant than dense populations. Reduced seed rate caused a slight reduction in yield in one case, a year of very poor establishment where the critical canopy size for development of a sufficient pod canopy was not reached the following spring. Similarly, delayed sowing (from the end of August to the end of September) produced no reduction in yield in two out of four cases, although slight reductions in yield were recorded in the other cases due to too small canopies. In the other instances, sufficient growth to reach the optimal canopy size was possible even with late-sown crops, whereas early-sown crops may have been too large. Mechanical defoliation in February usually caused numerical increases in yield, which were greater in larger (early sown, high seed rate) canopies. However, none of the canopies produced were as large (maximum LAI 3.5) as anticipated so the benefits from mowing were smaller than those identified in previous work. An example of these agronomic effects is shown in Table 2 (1996 data)

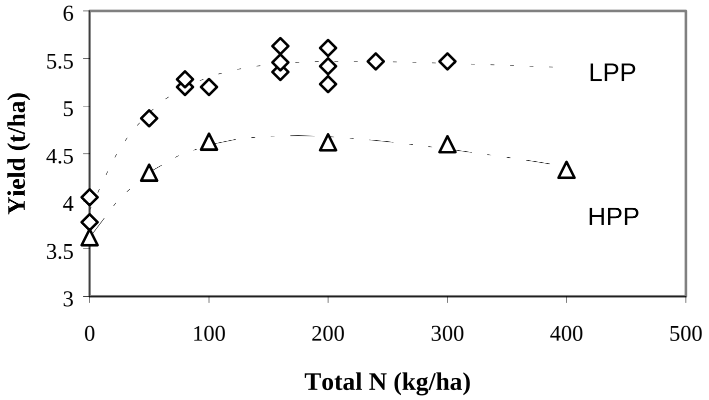
Table 2: Effects of sowing date, seed rate and defoliation on oilseed rape yields (1996)

Sown	Seed rate (m^{-2})	Plant Population[a] (m^{-2})	Yield (t ha^{-1})	
			Not Defoliated	Defoliated
Early	120	114	4.03	4.35
(31/08/95)	60	65	4.37	4.46
Late	120	111	4.08	4.11
(25/09/95)	60	71	4.50	4.11

Sowing date x seed rate x defoliation (21 df)
SED = 0.329, LSD (5%) = 0.685, P = 0.954

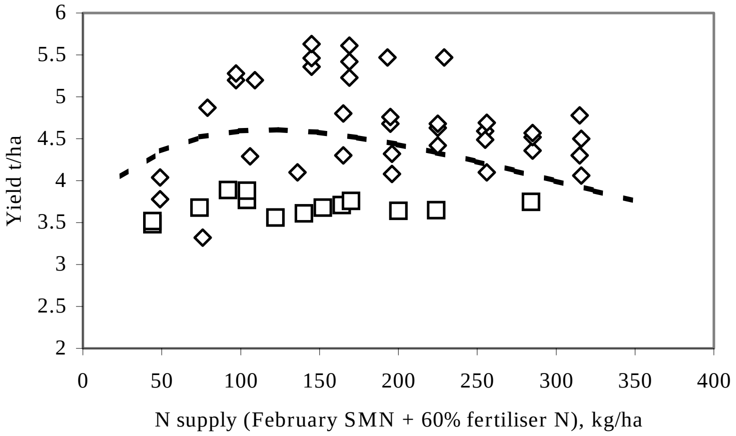
The response to nitrogen fertilisation was variable. Increasing soil nitrogen supply (including N fertilisation) generally increased canopy size, both by increased total green area and greater pod numbers (data not shown). The form of the yield response to nitrogen varied depending on soil mineral N levels from year to year. When SMN (<50 kg ha^{-1}) was low, the classic linear plus exponential yield response to nitrogen was observed (Figure 7) with extra yield gained from N fertilisation. However, when SMN was very high (e.g. 165 kg ha^{-1} in 1996), the response was shifted onto the decreasing part of the curve (data not shown) so that there was no yield benefit from N fertilisation. There was little benefit of early application of nitrogen (February) allowing later N applications (immediately pre-flowering) as a method of limiting excessive leaf and stem development, but providing N supplies for pod development.

Figure 7: Effect of N fertilisation on yield, Sutton Bonington 1997 (LPP = low plant population, main experiment, HPP = high plant population subsidiary experiment).



The linear plus exponential relationship of yield to estimated N supply (60% SMN in February + 60% of fertiliser N) showed an optimum supply of 125 kg ha^{-1} was needed to give the best yield potential, with over supply of N being detrimental to yield (Figure 8).

Figure 8: Effect of soil N supply on yield (diamonds = 1996, 1997 and 1998, squares = 1998, excluded from the curve fitting).



Given the availability of large amounts of SMN in some site x season combinations, the published N recommendations (up to 230 kg ha^{-1} fertiliser N, Anonymous, 1992) could cause considerable over-application. The margin of yield value over N costs (using a price of rapeseed of £110 t^{-1} and nitrogen of £0.40 kg^{-1}) was related to the N application rate by linear or linear plus exponential relationships, emphasising the deleterious effect of excess N on yield and loss of crop margin caused by over application. With all the data pooled, the optimum margin was found at an application of about 125 kg ha^{-1} N. An assessment of the effect on margins of zero N application, targeting a 125 kg ha^{-1} soil nitrogen supply (augmenting SMN with applied fertiliser only when necessary) or using the book recommendation, showed the targeted N to be most profitable, producing an average margin of £459 ha^{-1}. The next best strategy was zero N (£422 ha^{-1}) with the book recommendation producing the worst return (£400 ha^{-1}).

Study of the potential pest and disease management strategies for smaller canopies was relatively inconclusive as the study was complicated by seasonal factors resulting in similar canopy sizes and low pest and disease pressures. In 1998, yield was significantly reduced (up to 1.2 t ha^{-1}) by not controlling fungal disease, although the only significant differences in disease levels were greater stem and pod and light leaf spot (*Cylindrosporium concentricum*) infection in untreated plots with very low levels of all the other diseases. Insect activity was low, and there was no significant yield penalty from not controlling insects. In 1999, no significant change in yield was caused by any of the management strategies, and again disease and insect pressures were low. Calculation of the net margin of yield (assuming a price of 110 t^{-1} for rapeseed) over the costs of chemicals and applications showed that double prophylactic spraying for insecticide and fungicide resulted in the worst margin over a range of crops (Table 3). Therefore, there are opportunities to boost the profitability of oilseed rape by more selective spray management strategies.

Table 3: Margins of crop value over fungicide and insecticide (including application) cost for different crops and spray application regimes, 1998-1999

Year	**Sowing Date**	**Seed Rate**	**Yield (t/ha) and management**						
			Treatment	1	2	3	4	5	Crop Mean
			Fungicide[a]	U	M	P	P	P	
			Insecticide[a]	P	P	P	M	U	
1998	Early	120		407	456	443	439	436	436
1998	Early	60		419	445	402	414	468	430
1998	Late	120		332	342	327	321	327	330
1998	Late	60		358	332	352	363	400	361
Treatment mean				379	394	381	384	408	389[b]
1999	Early	120		304	318	267	310	330	306
1999	Early	60		262	248	220	297	289	263
1999	Early	120		332	312	258	238	235	275
1999	Early	60		273	242	221	243	234	243
Treatment mean				293	280	242	272	272	272[b]
Grand (strategy) mean				336	337	312	328	340	331[c]

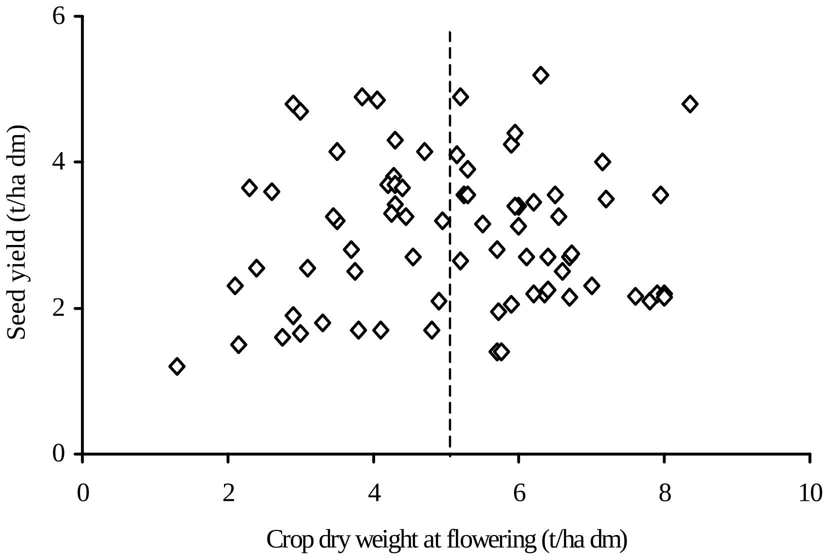
[a] P = prophylactic, M = managed, U = untreated [b] Yearly grand mean [c] Mean margin over spray costs (8 x 5 year.sowing date.seed rate combinations x spray strategies).

APPENDIX I: Effects of canopy size and architecture on yield of oilseed rape

1. Introduction

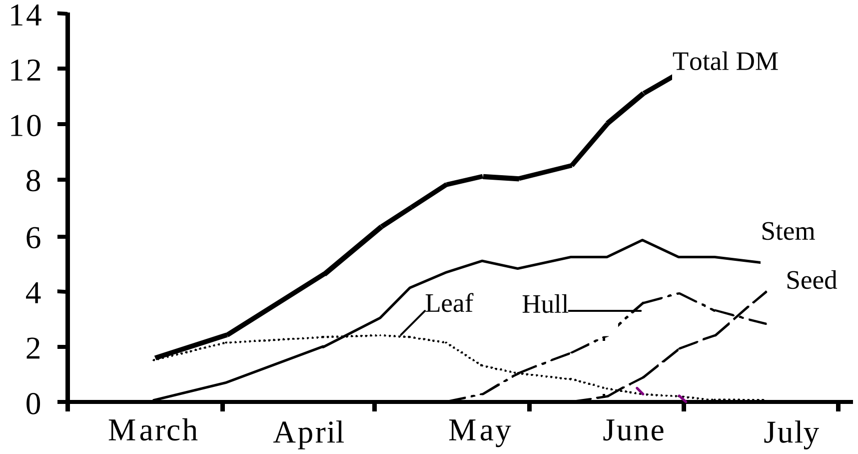
With most arable crops, such as wheat, there is a direct relationship between the amount of light intercepted by the leaves during the growing season and final yield (Gallagher and Biscoe, 1978). In winter (autumn-sown) oilseed rape (*Brassica napus*, L.) the situation is not so straightforward. 'Well grown' or ‘lush’ crops with prolific foliage growth in the spring, for example from early sowings and high seed rates, often fail to yield as well as expected. On the other hand, there is much anecdotal evidence that more ‘backward’ and ‘sparse’ crops, which might have been the result of poor establishment, frequently yield much better than expected. These are the very crops where ploughing-in and re-drilling may have been considered. A review of various data sets comparing total crop dry matter at flowering with the final harvested yield (Figure 1, reproduced from Stafford 1996) shows that there would appear to be no significant relationship between vegetative crop size (dry matter basis) and final yield in oilseed rape.

Figure 1: Mature seed yield of oilseed rape plotted against total crop dry weight at full flowering (adapted from Stafford, 1996). The dashed line shows the critical 5 t ha^{-1} flowering biomass identified by Mendham *et al.* (1981)



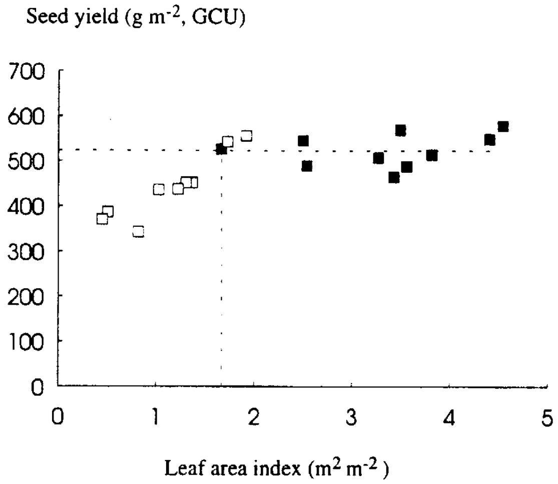
A closer inspection of the dry matter partitioning between the various organs of oilseed rape in a detailed study of a crop of Capricorn (Stafford, 1996) identified a possible explanation for the scatter shown in Figure 1. After flowering, most leaf material rapidly senesced before the phase of dry matter deposition accounting for seed yield and the dry weight of stems remained constant throughout this phase (Figure 2), indicating that no stem reserves were retranslocated to contribute to yield. This is unlike cereals where up to 30% of the grain yield may be supplied by remobilisation of stem carbohydrate reserves (Foulkes *et al.*, 1998).

Figure 2: Dry matter partitioning in a crop of winter rape cultivar Capricorn grown at Sutton Bonington, 1993 (Modified from Stafford, 1996).



The major source of assimilate for seed yield must therefore be derived post-flowering by photosynthesis in the green pod walls and branches, shown by Norton *et al.* (1991) to account for 95% of photosynthesis during seed formation, with a small amount of dry matter retranslocated from pod hulls (Stafford, 1996). It would therefore seem that the structure and photosynthetic efficiency of the pod canopy are by far the most important factors in determining seed yield, and that the main function of leaves and stems is to support and develop the reproductive canopy. However, early work by Mendham *et al.* (1981) showed that a certain critical value of crop size at full flowering was required for maximum yield, with greater than about 500 g m^{-2} (5 t ha^{-1}) dry matter needed at full flowering (shown by the dashed line on Figure 1). With late sown crops, where crop size was often less than the critical value, yield increased linearly with increase in crop size at flowering. No such relationship was found with early-sown crops which all exceeded the critical value. Habekotté (1997) re-analysed the data of Mendham *et al.* and presented it in terms of leaf area index (LAI) just before flowering. For late - sown crops, yield increased linearly with increase in LAI before flowering, up to an index of about 1.75. For early sowings, all crops exceeded the critical value of 1.75 by flowering and there was no relationship between LAI (to values over 4.5) and yield (Figure 3, from Habekotté 1997). This may at first sight appear to disagree with Figure 1, although with this data there were indications that crops with less than 2 t ha^{-1} dry matter at full flowering were unable to produce yields > 4 t ha^{-1}. There were also very few crops with very small dry matters compared to the Mendham *et al.* data. However, both of these data sets indicate no yield advantage from the very large, lush canopies of traditionally perceived 'good' crops.

Figure 3: Relationship between leaf area index before flowering and yield identified by Habekotté (1997) from data of Mendham *et al.* (1981). Open squares show late-sown crops and closed squares show early-sown crops.



Work from a number of experimental programmes reported in the literature, and in previous work at the University of Nottingham (Mendham *et al.* 1981, Jenkins & Leitch, 1986, McWilliam *et al.* 1996, Stafford, 1996, Stafford *et al.*, 1996) indicates the probable mechanism by which smaller pod canopies can produce comparable or significantly better yields than larger canopies growing under the same conditions of incident radiation. The key to the better than expected performance of treatments that produce more open pod canopies is that they would appear to produce more seeds per pod, whereas in the thicker canopies, light penetration to the lower pods is poorer. There is thus less assimilate available per pod for seed filling, so fewer seeds are formed or retained in each pod. The effects of fewer seeds per pod may more than offset the increased pod numbers in denser canopies and the improved retention of seeds can result in about 0.5 t ha^{-1} more yield in sparser canopies. Denser canopies are also more prone to lodging, resulting in compression of the pods into a dense layer and further reduction in light penetration to the bottom pods. The data described above implies that 6-7,000 pods m^{-2} could be optimum. With current economic pressures and changes in arable area payments under Agenda 2000, the profitability of oilseed rape has decreased and there has been some debate about its future role in crop rotations. Table 1 shows the gross margins of a run of first to fifth wheat crops and low and high yielding crops of oilseed rape under Agenda 2000. Low yielding oilseed rape has a lower gross margin than any cereal, however a high yielding crop is second only to a first wheat crop. What is important however is the performance across the rotation as a whole. If we take a five year rotation and compare continuous cereals with a rotation of two wheats, oilseed rape and two wheats, this gives us gross margins of £472 ha^{-1} year^{-1} compared to £468 ha^{-1} year^{-1} for a rotation with a low yielding OSR crop and £501 ha^{-1} year^{-1} with a high yielding oilseed rape crop. The case for maintaining oilseed rape in the rotation is therefore weak unless a system of growing the crop can be found which avoids poor performing crops.

Table 1: Approximate gross margins for wheat and oilseed rape crops under Agenda 2000

	Wheat	Oilseed rape

	First	Second	Third	Fourth	Fifth	Low	High
Yield (t ha^{-1})	9.0	8.0	7.5	8.0	8.5	3.0	4.5
Price (£ t^{-1})	60	60	60	60	60	110	110
AAP[1] (£ ha^{-1})	214	214	214	214	214	214	214
VC[2] (£ ha^{-1})	220	230	240	240	240	200	200
Margin (£ ha^{-1})	534	464	424	454	484	344	509

[1] Arable area payment [2] Variable costs

2. Materials and Methods

2.1. Field Experiments

2.1.1.General experimental design

The hypotheses described in the Introduction were tested with detailed measurements made throughout the season of canopy architecture (leaf, stem and pod development and components of final yield), light capture and yield formation. Due to the time-consuming nature of growth analysis of oilseed rape, detailed measurements were carried out in a small number of contrasting canopies (***primary treatments*)** at both ADAS Rosemaund and Sutton Bonington. In addition, a greater range of ***secondary treatments***, at each site in each year, were examined in less detail to provide additional data to test the hypotheses.

2.1.2 Variety choice

The variety Apex was used throughout the trials because in 1995 it was the most widely grown variety (over 60% of the area) and was expected to remain in widespread use for the rest of the experimental programme. This was indeed the case, as in 1999 it still accounted for 45% of the rape area. Apex has an 'intermediate' growth habit, midway between the French types *eg.* Bristol with generally larger canopies and the British types with generally smaller canopies, *eg*. Inca.

2.1.3. Plot size and layout

At Sutton Bonington, plots were 6 m x 36 m in 1996, 18 m x 8 m in 1997, 6 m x 22 m in 1998 and 12 m x 24 m in 1999. The design was a randomised block design with four replicates and with nitrogen application as the sub-plots. At ADAS Rosemaund, plots measured 4 m x 36 m, 6 m x 24 m, 3 m x 24 m in 1996, 1997 and 1998 and 1999 respectively. Larger plots were used in the first two years at ADAS Rosemaund as more growth analyses were undertaken. In the final two years, smaller plots were used as fewer growth analyses were done, but more treatments were included .The design was a split-plot with four replicate blocks. Time of sowing was the main plot with factorial combinations of seed rate x defoliation (1996, 1997) or seed rate x management strategy (1998, 1999). At ADAS Rosemaund, plots were drilled with an Accord pneumatic drill in 1996 and 1997 and a double width Wintersteiger plot drill in 1998 and 1999 at 120 or 60 seeds m^{-2}. At Sutton Bonington, plots were marked out in a farm crop drilled at approximately 120 seeds m^{-2}, to avoid problems with patchy drilling and emergence of plots and to allow large plots for growth analysis sampling.

2.1.4. Husbandry

The locations, soil types, and sowing dates of the field trials are shown in Table 1. Harvest was in the last week of July or the first two weeks of August.

Table 1: Location and soil type of canopy management trials, 1995-1999

Site	**Year**	**Location**	**Soil type**		**Sowing date**
SB	1996	Pasture Lane	Fladbury		09/09/95
	1997	Field 31	Dunnington Heath		02/09/96
	1998	Dewsbury’s	Dunnington Heath		02/09/97
	1999	Pasture Lane	Fladbury		30/08/98
ADAS	1996	Big Yard	Bromyard	Early	31/08/95
				Late	25/09/95
	1997	Stoney	Bromyard	Early	29/08/96
				Late	24/09/96
	1998	Holbach	Bromyard	Early	05/09/97
				Late	01/10/97
	1999	Bottom Holbach South	Bromyard	Early	06/09/97
				Late	01/10/97

The crops were managed using standard agronomic techniques including prophylactic applications of herbicide, fungicide and insecticide (except ADAS Rosemaund 1998 and 1999 where the management strategy varied and is shown in Appendix IV).

2.1.5. Soil mineral nitrogen determination

Soil cores (90 cm deep) were taken with an auger from 10 locations in a ‘W’ pattern across the relevant experimental area in February each year. The 0-30 cm, 30-60 cm and 60-90 cm horizons from the 10 locations were pooled to form three separate samples, which were frozen at –20°C on return to the laboratory. The samples were analysed for moisture content, nitrate and ammonium N (mg kg^{-1}) at ADAS laboratories, Wolverhampton. The total amount of mineral (ammonium and nitrate) N (mg kg^{-1}) in 90 cm was calculated and converted to kg ha^{-1} N with a conversion factor of 4 (assuming a soil bulk density of 1.3 g cm^{-3}).

2.1.6. Nitrogen application

Nitrogen was applied as ammonium nitrate prills as a split application in the spring at both sites. Seedbed nitrogen was also applied differentially to some plots at Sutton Bonington in the 1996/1997 experiment year. The dates of the applications are given in Table 2, which also shows the soil mineral N residues recorded in February. The rates of N application for the different treatments at Sutton Bonington are given in the description of the experimental design in Appendix III and for Rosemaund are shown in Table 2.

Table 2: Soil mineral N residues in February and nitrogen application dates.

Site	**Year**	**Soil Mineral N**	**Date of nitrogen application**[1]		
		(kg ha^{-1} to 90 cm)	**Autumn**	**Spring#1**	**Spring#2**

SB	1996	165	-	01-02/03	25/03
	1997	49	18/11	07/03	07/04
	1998	44	-	04/03	27/03
	1999	76	-	24/03	29-30/4
ADAS	1996	no data	29/2 (43)	19/03 (53)	25/04 (70)
	1997	100	-	12/03 (83)	01/04 (140)
	1998	95	-	21/03 (82)	21/04 (74)
	1999	88	16/10 (44)	23/02 (101)	-

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[1] Rates for ADAS Rosemaund (kg N ha^{-1}) are given in brackets, for Sutton Bonington they are summarised in description of experimental treatments in Appendix III.

2.2. Growth analysis

2.2.1. Sample collection

Growth analyses were done on the three most uniform replicates only, after visual assessment in the spring. One half of the plot length was allocated for biomass sampling and growth analysis whilst the other half was retained for combine yield. Samples were taken at two-week to one month intervals throughout crop development from February. The main detailed growth analyses were done immediately prior to flowering (April/May), mid-flowering (May/June) and 4-6 weeks after the end of flowering (July).

Samples were removed from 1.0 m^2 quadrat areas. To avoid local bias in the selection of samples, the sample was taken from pre-determined areas from one dedicated end of the experimental plots. At least 0.5 m was left between sample areas, which were also at least 1 m from the ends and edges of the plots and from tramlines.

All the above ground material within the quadrat area was recovered. At early timings, plants were pulled up and the roots were cut off. In later samplings, secateurs or a sharp serrated knife were used to cut off plants at the soil surface. All the above ground material was collected and placed as quickly as possible into a plastic bag. The stems were placed in the bag such that the lower portion (*i.e.* the end most contaminated with soil) was at the bottom of the bag, reducing the proportion of the crop contaminated with soil and hence reducing the washing time.

After all the material was collected, the bag was sealed to prevent the laminae drying out. The measurement of the projected areas of laminae was completed as soon as possible to prevent wilting. Samples were stored in a cold room at 4 - 6° C for up to 5 days before analysis.

2.2.2 Sample processing.

If contaminated with soil, the samples were washed gently under a running tap. The plant material was shaken thoroughly and was gently dried with paper towels to remove excess water.

(i) Pre-flowering

The fresh weight of the whole sample was determined. The total plant number was recorded by counting into 10 piles. For two randomly selected piles (SS1), the fresh weight was recorded; if it was not approximately 20% of the total fresh weight, the plants were re-subsampled. For the remainder (8 piles = SS2), the fresh weight was recorded and the samples were cut up into metal oven trays and dried at 85^{o}C for 48 hrs. The dry weight was recorded and the samples were retained for nitrogen analysis. When remainder samples were large, the SS2 sample was taken as a further 2 piles to be 20% and the remaining 60% was discarded.

The SS1 sample was divided into green leaf, non-green (dead) leaf, green stem and non green stem (where appropriate). The fresh weights of the different fractions were recorded. The projected areas of all green material were measured with a Licor or Delta T electronic area meter. All fractions were dried at 85^{o}C for 48 hours, the dry weight was recorded and the samples were stored for N analysis. Green area indices were calculated for each fraction and the total crop. Stems were assumed to be perfect cylinders, and the projected area was multiplied by $\pi/2$ so that half the surface area contributed to GAI (Bilsborrow, 1985).

(ii) Post-flowering

Sub-sampling was carried out as in (i).

For the SS1 sub-sample, the plants were split into at least two layers: pod (including 95% of the pods) and stem, and the depth and fresh weight of each layer was recorded. Earlier in the experimental programme, the pod layer itself was subdivided. For each layer, the green leaves, non-green leaves, flowers, buds pods and stems were divided into separate trays and the fresh weight was recorded. The numbers of flowers, buds and pods in each layer were counted. The projected areas for all SS1 fractions and dry weights were recorded as in (i) *(iii) Pre-harvest*

The number of plants in a 1.0 m^2 quadrat sample was counted. All seed were threshed out, and haulm and seed plus pod wall was separated. The total fresh weight of haulm was recorded. A 150-200 g subsample of haulm was accurately weighed and put in an oven tray. The seed and pod halves were separated, and the total fresh weight of seed was recorded. A sample of 1000 seeds was accurately counted with a seed counter, the fresh weight was recorded and placed in an oven tray for drying at 85°C. The total fresh weight of pod halves was measured and a sub-sample of ~ 50 g was weighed. The numbers of pod halves were counted and put into an oven tray for drying at 85°C.

2.2.3 Calculations

For green areas of stems and pods, these organs were assumed to be perfect cylinders and half of the cylinder was assumed to contribute to light interception (Bilsborrow, 1985). Therefore, projected areas were multiplied by $\pi/2$ (1.57).

Fertile pod numbers per square metre were calculated from the growth analyses. The seed numbers per square metre were calculated from the yield in g m^{-2} (yield in t ha^{-1} * 100) divided by the thousand seed weight (g)/1000. The number of seeds per pod was calculated by the number of seeds m^{-2} divided by the number of pods m^{-2}.

2.3 Light interception

At each biomass sample timing and for selected treatments light interception was recorded. A reading was taken within the biomass sampling area and a second reading for the rest of the plot. Each of these readings was an average of five constituent readings.

(i) Pre- flowering

Using 2 ceptometers, 5 concomitant readings for incident radiation, reflected (inverted above crop) and transmitted (ground level) were taken.

(ii) Post-flowering

Using 2 ceptometers, 5 concomitant readings for incident and reflected (inverted above crop), transmitted at ground level and base of pod layer (95% of pods above) were taken

2.4 Lodging

The percentage plot area lodged or leaning on each visit was recorded if the plots were affected.

2.5 Yield

All plots were harvested with a Sampo plot combine with extension bed and side knives. The final cleaned seed yield was expressed at 91% dry matter after moisture content determination

3. Results and Discussion

3.1. Effects of plant population on compensatory growth in oilseed rape.

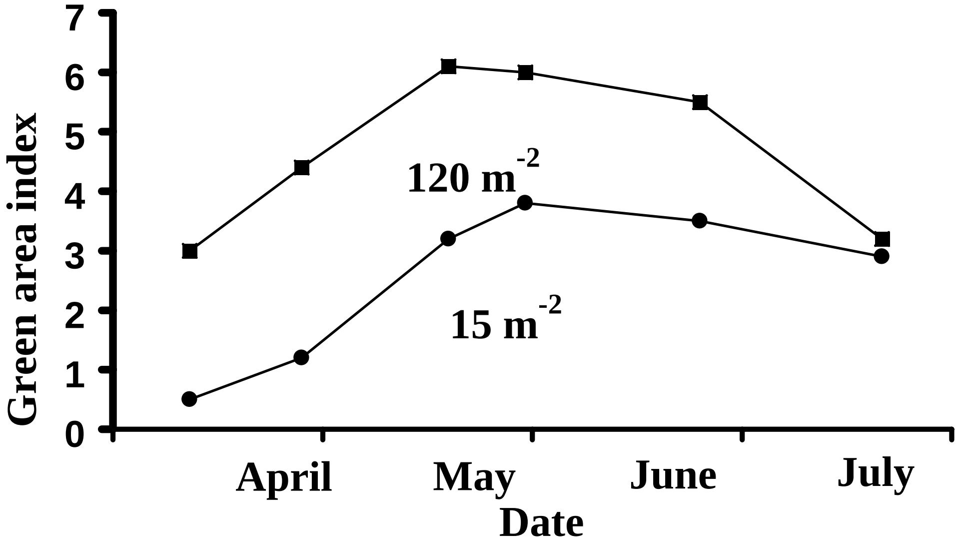
No detailed studies of plant population were possible in the current project (see Appendix II: only two seed rates were available at Rosemaund from 1995-1999 and Sutton Bonington trials were conducted in farm crops). However, in previous HGCA-funded work (McWilliam *et al*., 1996; McWilliam, 1998), the growth and yield components of a series of crops with populations ranging from 7-120 plants m^{-2} were studied in 1992 (Table 3).

A graph of the green area indices of selected crops throughout development is shown in Figure 1. With the lower populations, canopies were smaller throughout development (maximum of 3.5 units at 7 plants m^{-2}) whereas at higher populations, the canopy was larger (maximum 6.5 at 120 plants m^{-2}).

Table 3: Yield and yield components of crops of differing plant population grown at Sutton Bonington (taken from McWilliam *et al*., 1995)

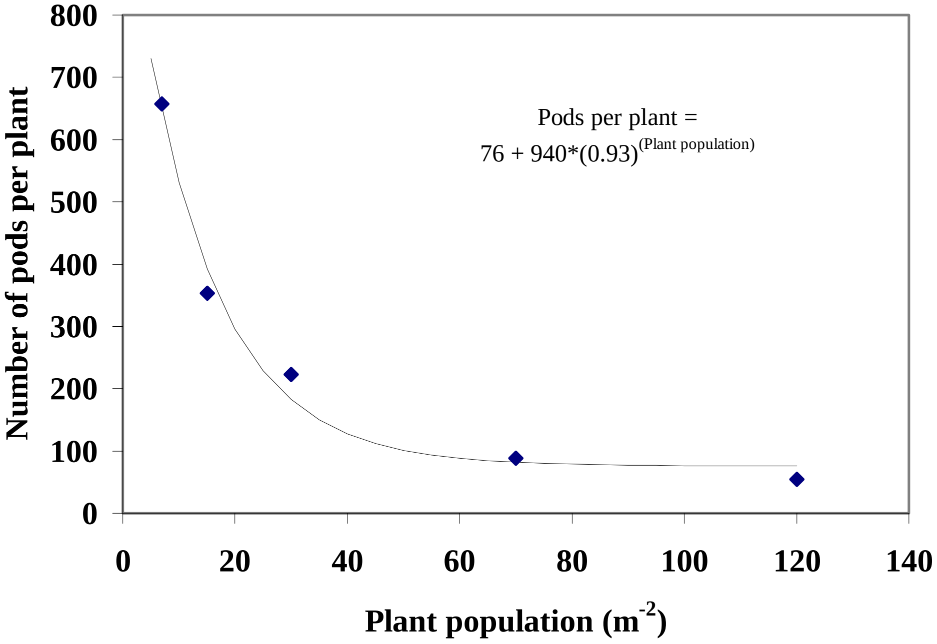
Plant population (m^{-2})	**Yield @91% dm (t ha^{-1})**	**Pods m^{-2}**	**Pods plant-^{1}**	**Seeds pod^{-1}**	**1000 seed weight (g)**	**Total biomass (t ha^{-1})**
7	3.60	4600	657	16	4.78	10.0
15	3.40	5300	353	15	4.49	10.0
30	3.70	6700	223	13	4.40	11.5
70	2.90	6200	89	10	4.84	11.0
120	3.00	6500	54	10	4.56	11.5

Figure 1: Green area indices throughout development of crops with populations of 120 plants m^{-2} and 15 plants m^{-2}.



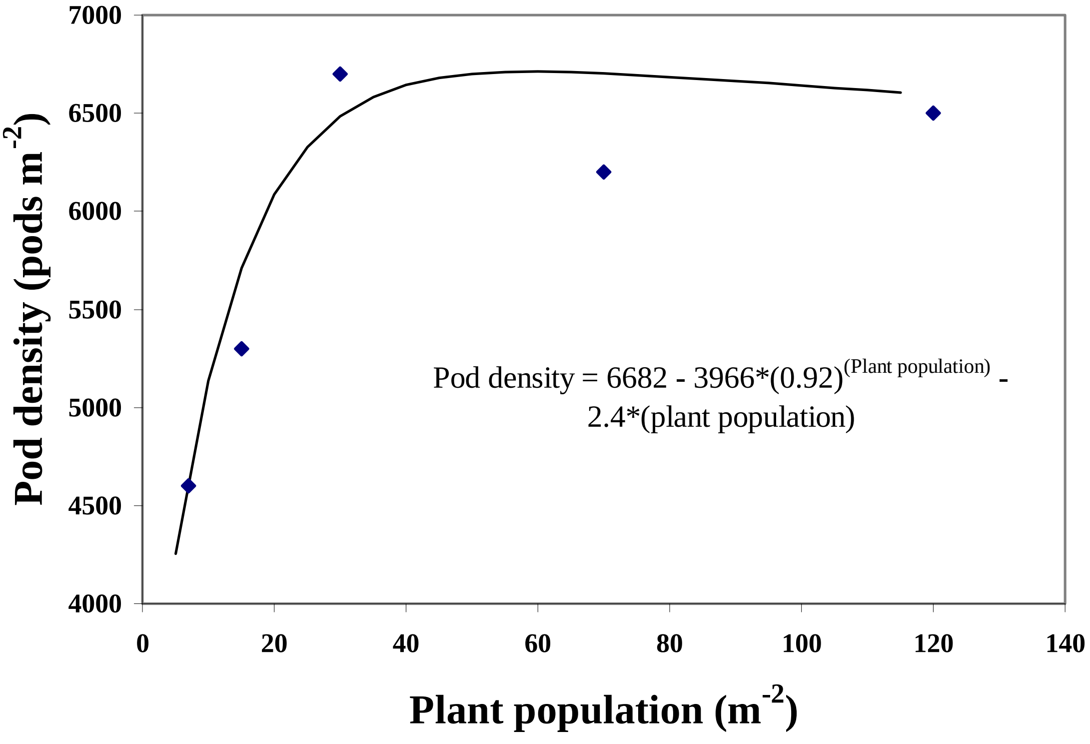
Nevertheless, the crops with smaller canopies (< 30 plants m^{-2}) out-yielded the larger crops. It is evident from the data that oilseed rape is able to largely compensate for smaller populations and sparser canopies by producing more pods per plant, which retain more seeds per pod. Using the data from Table 3, the effect of plant population on numbers of pods per plant can be plotted. A straightforward power relationship (Pods per plant = $75.8 + 940*(0.93)^{(\text{Population})}$) gave a significant ($P<0.05$) fit on regression analysis accounting for 97% of the variance. Thus, reduction in plant density below 80-100 plants m^{-2} caused a rapid increase in the number of pods per plant (Figure 2).

Figure 2: Effect of plant population density on numbers of pods per plant



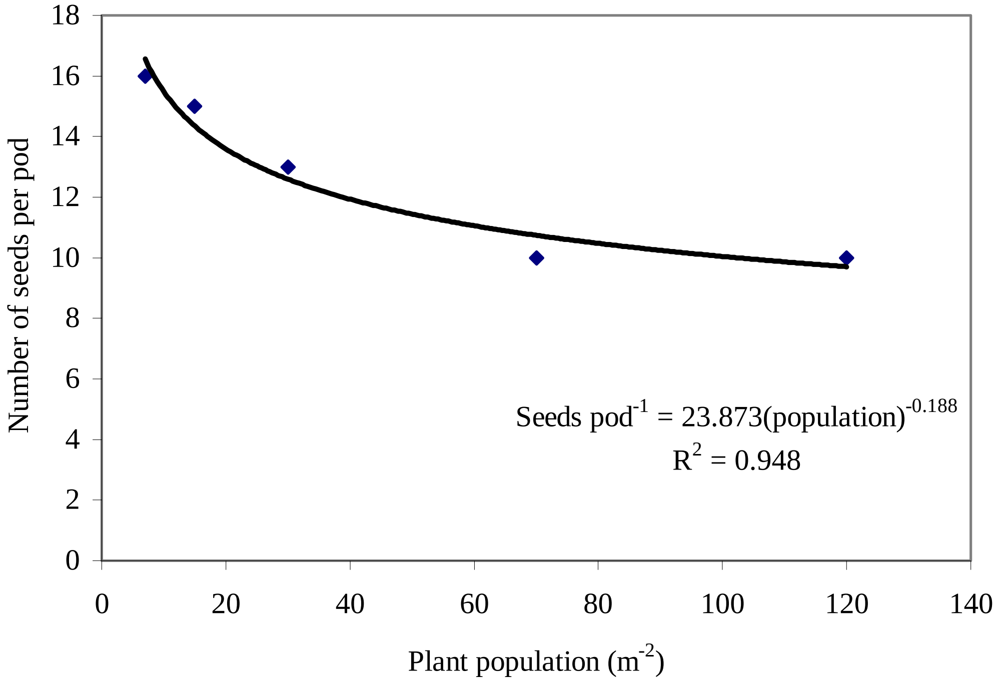
A linear plus exponential function (Figure 3) provided the best fit to the data to explain effect of plant population on pod density (pod density = 6682 – 3966*$(0.92)^{(\text{plant population})}$ – 2.4*(plant population)), although the relationship was not significant ($P = 0.41$), accounting for 58% of the variance. However, it indicated an apparent maximum or optimum number of pods developed, reached at 30-50 plants m^{-2} with a plateau or slow decline in pod numbers with subsequent increase in plant population. In this instance the optimum pod numbers were about 7,000 m^{-2}, but it is likely that this could vary with season. This data thus demonstrates the ability of oilseed rape to produce sufficient pod numbers from relatively small populations, far lower than the commercial norm of 80-100 plants m^{-2}. Increasing plant population does not increase pod numbers per square metre due to the decline in pod numbers per plant at high populations.

Figure 3: Effect of plant population density on pod density



A strong power regression relationship could be fitted to the data to explain the effect of population on numbers of seeds per pod (Figure 4). The relationship was strongly significant ($P<0.001$) with the equation seeds $pod^{-1} = 23.9*(\text{population})^{-0.19}$ accounting for 95% of the variance. The equation gives a maximum of 24 seeds per pod at a spacing of 1 plant m^{-2} and about 10 seeds per pod at 80 plants m^{-2}.

Figure 4: Effect of plant population on numbers of seeds per pod



A just non-significant linear relationship for the effect of pod number per m^2 (pod density) on seed number per pod, given by the equation seeds pod^{-1} = 27.5 - 0.0025*(pods m^{-2}) (Figure 5) could also be derived (P = 0.11, accounting for 52% of the variance).

The theoretical maximum number of seeds per pod (at biologically nonsensical pod densities of 1 pod m^{-2}) was 27 and as the pod density increased, the number of seeds per pod was reduced (to about 8 seeds per pod) at a pod density of 8000 m^{-2} due to the reduced amount of light available per pod for photosynthesis and consequently reduced assimilate to support seed growth. The maximum number of seeds per pod at 1000 pods m^{-2} (likely from a population of 1 plant m^{-2}) would be 25, very similar to the maximum number calculated from the plant population relationship above. This phenomenon has been observed by other researchers (Mendham *et al.* 1981, Stafford *et al.*, 1996). The ability of the crop to compensate for a sparser canopy and fewer pods depends on the linear relationship between pod density and the number of seeds per pod. If this relationship is shallow (*i.e.* high pod density causes small changes in seed number per pod) then the crop would be less able to compensate for reduced pod numbers. On the other hand, the deleterious effect of very high pod densities on yield would be less severe than if the relationship were steeper. A steeper slope would indicate a greater capacity to compensate for lower pod numbers and a more deleterious effect of pod density on yield.

Figure 5: Effect of pod density on numbers of seeds per pod

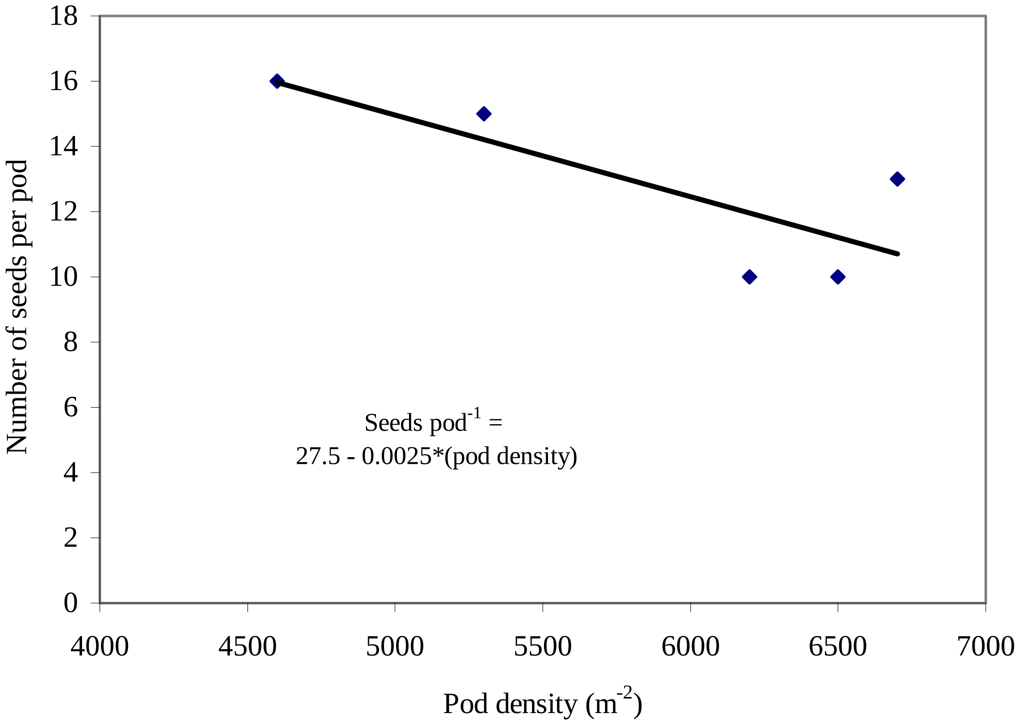
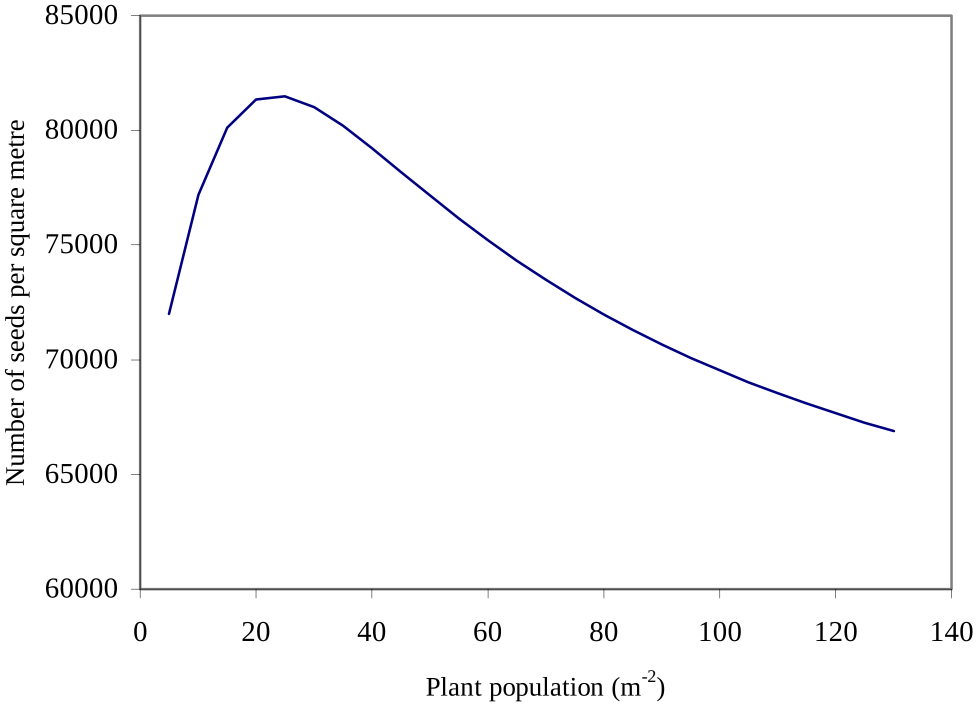


Figure 6: Theoretical effect of plant population density on seed numbers per square metre



The product of the number of pods m^{-2} and the number of seeds pod^{-1} gives the number of seeds m^{-2} (the prime determinant of yield, when multiplied by average seed weight). Thus a theoretical function for seed numbers m^{-2} in terms of plant population can be derived from the product of the equations for the effects of plant population on the number of pods m^{-2} (linear plus exponential) and numbers of seeds pod^{-1} (power), which is shown in Figure 6. Seed numbers per square metre increased rapidly from around 72,000 m^{-2} at low plant populations and were at their highest at low plant populations of around 20 - 25 plants m^{-2}: with increase in plant population above 20 m^{-2} seed numbers fell to about 69,000 m^{-2} at populations of 120 plants m^{-2}, a rate of 150 seeds lost per extra plant per m^{2}. Assuming minimal effects of plant population on mean thousand seed weight (and no significant relationship could be found, with the plotted values forming a scatter), then final yield also shows the same linear plus exponential relationship with plant population. Thus, yield can be expected to increase rapidly with populations from 1 – 25 m^{-2} and thereafter decline with increased plant populations as seed numbers per square metre fall. From the relationship above and assuming a seed weight of 0.0045 g, the decline in yield could be expected to be 0.00675 t ha^{-1} per additional plant above a population of 25 m^{-2}. This could equate to a 0.675 t ha^{-1} difference between populations of 25 and 125 m^{-2}. However, a linear plus exponential fit to the experimental data was not significant ($P = 0.80$), with the residual exceeding the variance of the response variate (data not shown). However, the theoretical relationship supports the theory that equivalent or improved yields may be derived from smaller canopies, such as those produced by smaller plant populations, because of their capacity to produce similar numbers of fertile pods to larger canopies, but more seeds pod^{-1} compared to larger canopies. Maximum seed yield would appear to come from 5-6,000 pods m^{-2} supported by 15-50 plants. As there may be problems with weeds (*e.g.* cleavers *Galium aparine*) and pigeon pressure, establishment of crops in the lower range may not be a feasible target, with populations of 30-50 plants m^{-2} probably preferable. Although these relationships explain the yield variation between differently sized canopies in a given year, the optimum pod number may vary from year to year depending on incident light levels; for example, in a bright year the effect of pod density on seed numbers per pod would be expected to be smaller, as more photosynthesis would be possible by a larger proportion of the canopy. Due to the plasticity in the yield components it is therefore possible in some circumstances for good yields to be achieved from relatively dense pod canopies (albeit with higher harvest index due to the reduced number of seeds per pod) providing the canopy remains upright and receives a high light intensity.

The ability of rape to compensate so thoroughly for reduced plant population (i.e. to produce similar numbers of pods from widely varying canopy sizes) can help to explain the relatively small differences between some of the treatments studied in Appendix II and the capacity of both small and large canopies to yield well under given conditions.

3.2. Effects of crop size before flowering on yield.

Understanding of the compensatory growth discussed above also helps to interpret the results of Mendham (1975), Shipway (1981) and Mendham *et al.* (1981) and the following work in this project. In Mendham's work, a relationship was identified between crop size at flowering and seed yield for late-sown crops only, with linear increase in seed yield as crop size increased at flowering. However, this relationship was not seen for early-sown crops. The data was re-presented in terms of leaf area index (LAI) before flowering by Habekotté (1997) (Summary, Figure 3). To achieve maximum yield, a LAI of about 1.75 before flowering was required, with reductions in yield if LAI was limited by late sowing (due to the limited amount of growth late-sown crops could make in spring in some years). All early-sown crops achieved LAIs above the threshold value, and there was no significant relationship between LAI and yield for early sown crops: thus similar yield, due to the capacity to produce similar pod numbers, could be achieved from widely differing canopies.

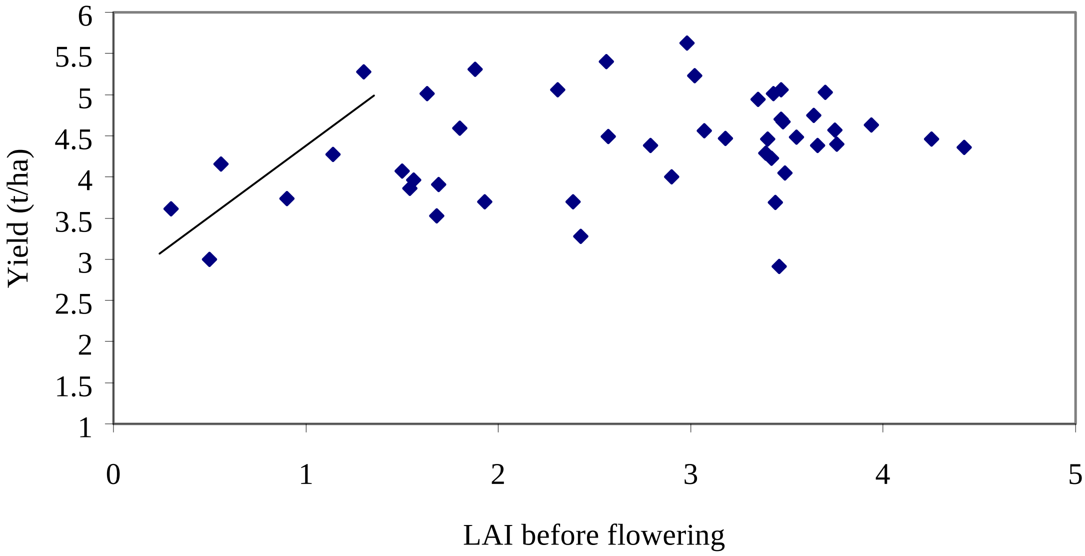
Detailed growth analysis was completed on a subset of the crops grown during 1995-1999. The crops analysed are summarised in Table 4. Data comparing LAI before flowering and yield for the crops for which detailed growth analysis was done in the current research programme is shown in Figure7.

Table 4: Crops studied by detailed growth analysis

Year	Site	Crops analysed
1996	Rosemaund	Early 120 seeds m^{-2}, Late 60 seeds m^{-2}
	Sutton Bonington	0, 100, 200 kg ha^{-1} N
1997	Rosemaund	Early 120 seeds m^{-2}, Late 120 seeds m^{-2}
	Sutton Bonington	0, 100, 200, 300 kg ha^{-1} N
1998	Sutton Bonington	0, 100, 200 kg ha^{-1} N

The data showed a similar relationship to that demonstrated by Habekotté (1997) using Mendham *et al.*'s (1981) data. Few LAIs before flowering were smaller than the 1.75 threshold identified by Habekotté (1997). Although there was an indication of reduced yield with LAI < 1.75 before flowering, the regression relationship between LAI (data < 1.75) and yield was not significant (P = 0.124) and accounted for only 11% of the variance. Even with small pre-flowering LAIs yields exceeding 5 t ha^{-1} were possible with minimum yields of about 3 t ha^{-1}. With the data comparing LAI > 1.75 with yield there was no significant relationship at all, with a broad horizontal scatter and yields between 3 - 5.5 t ha^{-1} possible from LAIs between 1.75 – 3.5 before flowering. With very large pre-flowering canopies (LAI > 3.5) there was a slight indication that the capacity to achieve the highest yields (> 5 t ha^{-1}) was limited.

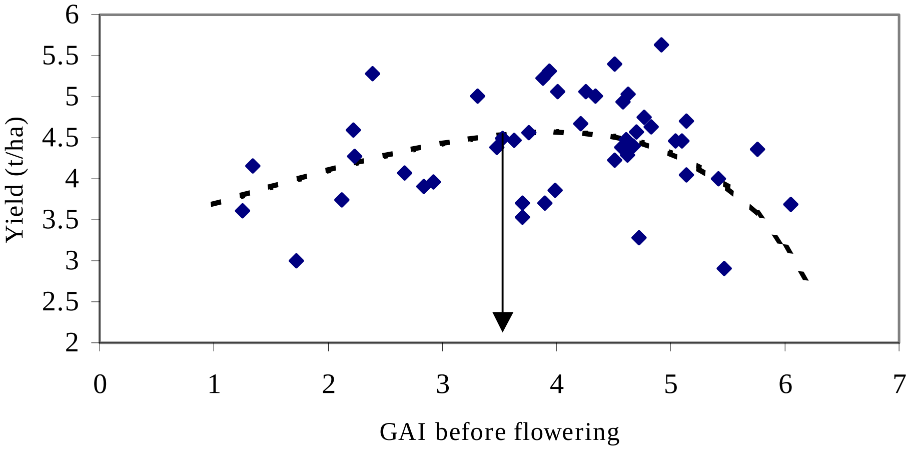
Figure 7: Effect of leaf area index before flowering on yield



A linear plus exponential fit to the data was not significant (P = 0.085). The relationship between total green area index, GAI (*i.e.* including stems in the assessment of photosynthetic area) before flowering and yield was very similar to that with LAI (Figure 8). Again, there was an indication of a critical crop size required by flowering, with evidence that GAIs < 3 before flowering could limit yield. However the linear regression relationship (GAI data < 3) was non-significant (P = 0.325), accounting for only 1.5% of the variance. With GAIs > 3 there was no linear relationship to yield, with a broad horizontal scatter of points. Yields of around 3 - 5 t ha^{-1} were possible with GAIs from 3-5, although there was a stronger indication that GAI > 5 before flowering limited yield, with the maximum yield of crops with GAI > 5 before flowering about 4.5 t ha^{-1}. Fitting of a significant (P = 0.034) linear plus exponential regression, accounting for 12.6% of the variance, was possible (Figure 12: yield = 3.147 – 0.21*(2.21)^{GAI}+ 0.479*GAI) emphasising the indications of limitations in yield by too small or too large pre-flowering canopies.

The optimum pre-flowering GAI for yield could be determined from the maximum point of the curve at a pre-flowering GAI of about 4.2. However, with pre-flowering GAIs from 3 – 5 there was little difference in the range of yields possible, with indication of limitation in yield by GAI <2 or > 6. This is probably in part due to the interaction of canopy size with incident radiation conditions in a given site x season combination. In bright years, a larger canopy size would be optimal whereas in dull years a smaller canopy size would be optimal

Figure 8: Effect of green area index before flowering on yield



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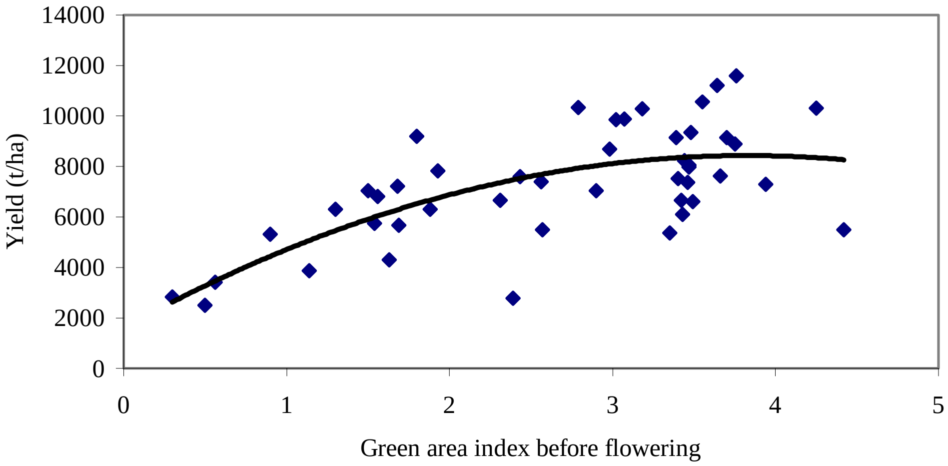
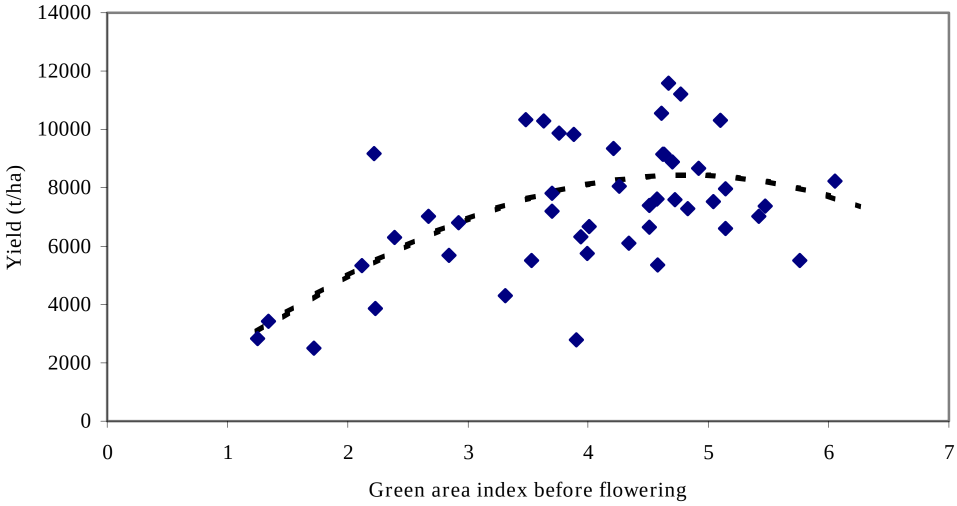
The reasons for the above relationship between pre-flowering crop size and yield are evident after consideration of the effect of crop LAI before flowering on the numbers fertile of pods m^{-2} produced after flowering. Figure 9 shows that a significant ($P < 0.001$) quadratic relationship accounting for 45% of the variance could be fitted to explain the effect of pre-flowering LAI on pod density (pod density = 1615 – 466*LAI^{2} – 3562*LAI.

Figure 9: Effect of leaf area index before flowering on fertile pod density



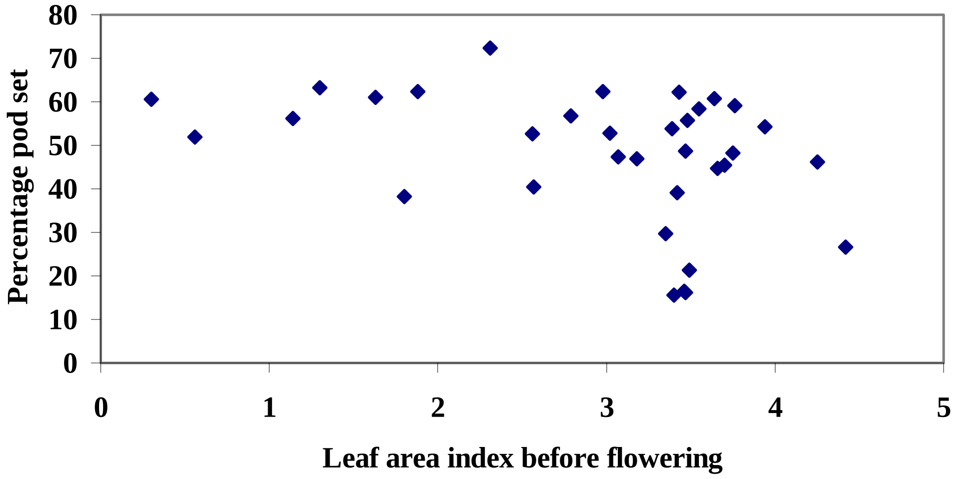
With LAIs below the critical value of 1.75, pod density was usually less than 6,000 m^{-2} and very low pod densities limited yield even when high numbers of seeds per pod were set. With pre-flowering LAI values > 1.75, greater than 6,500 pods per m^{-2} were almost always set, with maximum values up to about 12,000 pods m^{-2} possible. There was a slight indication that with pre-flowering LAIs > 4, final fertile pod numbers were lower than with LAIs < 4, due to the shape of the function. Plotting of a similar ($P < 0.001$) relationship was possible between GAI before flowering and pod density (Figure 10), although this accounted for slightly less of the variance ($24949 – 25806*(1.15)^{GAI} + 7076*GAI$, accounting for 28% of the variance).

Figure 10: Effect of green area index before flowering on fertile pod density



In this case pod numbers were usually limited if GAI was less than 2.5-3.0 before flowering, with the required > 6,000 pods m^{-2} usually produced with pre-flowering GAIs greater than this. However, there was a large amount of scatter about both relationships, indicating that other factors than pre-flowering vegetative canopy size (probably temperature, light and water availability during flowering) limit pod set. Again, there was an indication that limitations in pod density due to too large a canopy size started after a pre-flowering GAI of about 5. This could in part be due to reduced light interception due to the large mass of yellow flowers produced by large canopies, which other work has shown reflect or absorb 60-70% of sunlight radiation (Fray *et al.*, 1991). Thus in dense pod canopies, less light reaches the leaf layer to provide assimilate during pod set (*i.e.* before the pods are able to photosynthesise themselves). Due to the limitation in assimilate supply, pod set in dense canopies can be less efficient than in sparser canopies. This is demonstrated in Figure 11, which shows the effect of pre-flowering LAI on the efficiency of pod set. No significant relationship could be fitted, but there was a marked difference in the range of pod set possible (i.e. percentage of flowers producing fertile pods). In sparser canopies, consistently up to 60-70% of the flowers produced fertile pods. In denser canopies, the range was far greater from 15 - 60%. This range may again be explained by incident light conditions during flowering. In bright years, there would still be sufficient light to allow a high efficiency (about 60%) of pod set whereas in dull years the poor light penetration through the dense flower canopy would result in poor pod set with as few as 15% of flowers producing fertile pods.

Figure 11: Effect of leaf area index before flowering on percentage pod set



A very strong relationship was found between pod density and the number of seeds per pod, which was reduced drastically by high pod density. A significant (*P*<0.001) linear regression relationship (seeds pod^{-1} = 28.5 – 0.002*(pods m^{-2})), accounting for 79% of the variance, could be fitted (Figure 12). This relationship has been observed in the research of other authors (Mendham *et al.*, 1981, Mendham, 1995, Stafford, 1996) and is remarkably close to the relationship (seeds pod^{-1} = 27.5 – 0.0025*(pods m^{-2})) derived from the McWilliam *et al.* data. Because of the effects of crop size before flowering on subsequent pod density, weaker relationships could be plotted for the effects of LAI and GAI before flowering on the numbers of seeds per pod (Figure 17 for LAI: seeds pod^{-1} = 21.2 – 2.83*LAI, accounting for 33% of the variance and seeds pod^{-1} = 23.5 – 2.45*GAI accounting for 29% of the variance). Thus, crops with small canopies pre-flowering retained high numbers of seeds in each pod (> 20 for LAI <1) whereas large crops had fewer seeds per pod (< 10 for LAI > 4). This relationship explains the capacity of oilseed rape to produce similar yields from canopies of widely differing structures. Because of the increased numbers of seeds retained by each pod in sparser canopies, small canopies with few pods are able to produce equivalent numbers of seeds per square metre to large canopies, which have more pods but which retain fewer seeds per pod. Only with very small pod canopies is yield potential limited by too few pods (below about 4,000 pods m^{-2} if the target is 100,000 seeds of thousand seed weight 4.5 g giving a 5 t ha^{-1} yield). With very large canopies (>10,000 m^{-2}) yield is limited by too few seeds per pod. Thus it is evident that there is potential for growing smaller oilseed rape canopies.

Figure 12: Effect of pod density on seed number per pod

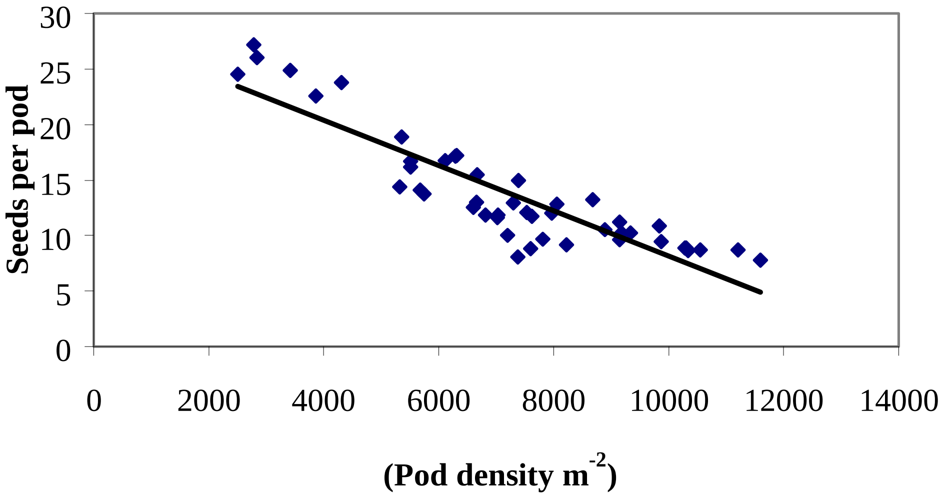
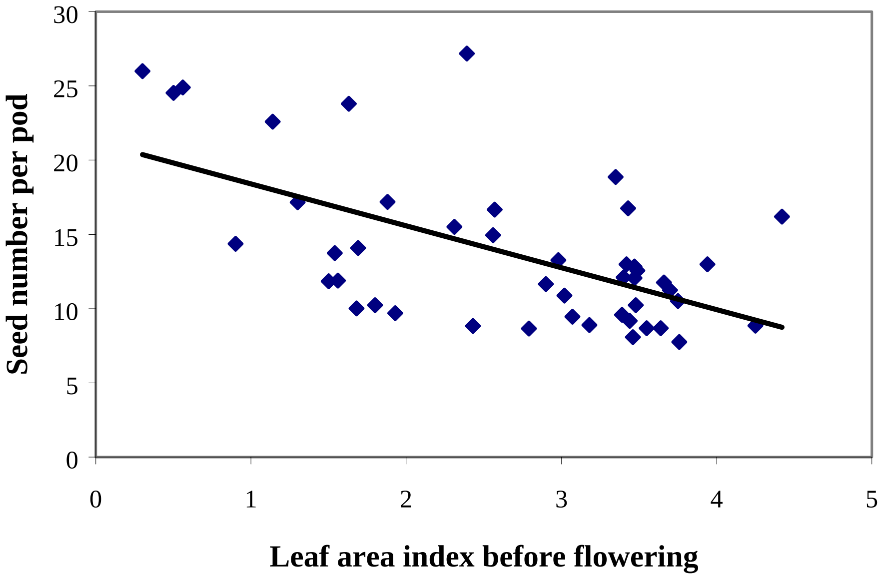


Figure 13: Effect of leaf area index before flowering on seed number per pod



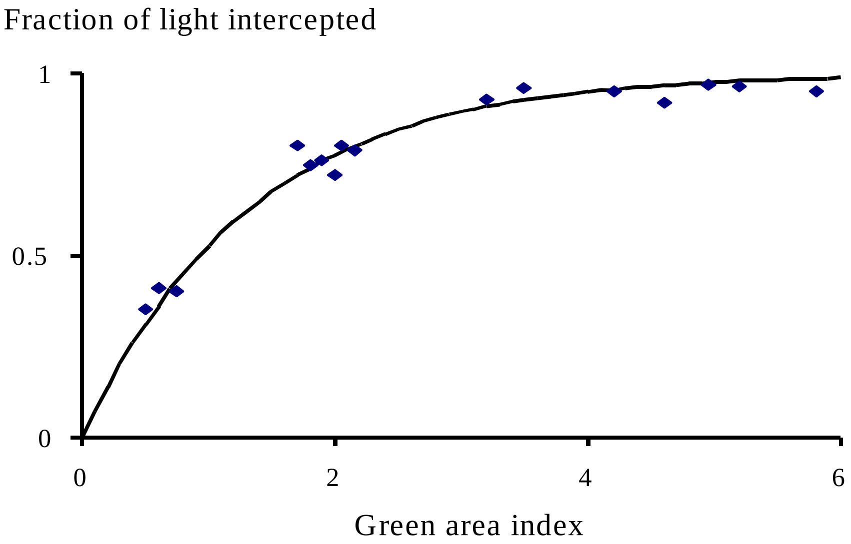
From these data it is evident that a GAI > ~ 3 (or LAI > ~ 1.75) before flowering is desirable to avoid limitation of yield by an undersized canopy (*i.e.* too few pods m^{-2} to capture enough sunlight and too few seeds m^{2}). On the other hand, significant reductions in yield were encountered with pre-flowering canopy sizes of GAI > 5. Although there was little yield penalty of pre-flowering canopy sizes of GAI > 4, these canopies produced more pods and fewer seeds per pod (having a poorer harvest index and requiring more nitrogen to generate the pods) and produced more flowers which could increase the risk of *Sclerotinia* infection *etc.*. A reasonable target canopy size for oilseed rape before flowering would therefore seem to be 3-4 (say, 3.5).

The relationship of pod density to seeds per pod would appear to be very robust and could be used to predict yield from pre-harvest measurements of pod numbers. The effect of crop size before flowering on subsequent pod density is less robust – presumably due also to the incident solar radiation and environmental conditions affecting the success of flowering.

3.3. Light interception

Study of light interception with variation in canopy size demonstrated that light interception in oilseed rape broadly obeyed Beer's law (Monteith, 1965) as in other crops such as wheat. The data show (Figure 14) that a GAI of about 3-4 was sufficient to intercept 90-95% of incident radiation and larger GAIs resulted in little extra light interception.

Figure 14: Fractional light interception with green area index (ADAS Rosemaund, 1996).



This correlates well with the GAI of 3 (LAI of 1.75) identified as the critical pre-flowering canopy size required for optimum yield; smaller canopies would not be making use of all the available light. As described in the sections above, variation in incident light may explain much of the scatter about the relationships relating canopy size and yield as the graphs consist of determinations from different site x season combinations. Within one site x season combination it can be expected that the relationships between pod density and seed number and yield would explain more of the variance but in this work there were insufficient numbers of crops analysed in each site x season combination for regression analysis. Returning to the general mode of light interception within crops, Beer's law states that the light transmitted by a layer *t* of a canopy, I_t is related exponentially to the incident light, I_o according to the green area index (GAI) of the layer and an extinction coefficient, *k*.

i.e. $I_t = I_o e^{-k\mathrm{GAI}}$ where e is Napier’s constant (2.718)

If we consider that there is a level of transmitted radiation (I_t) within the canopy below which photosynthetic material is below the light compensation point, then the green area index of the canopy required to attenuate incident radiation (I_o) to this value can be calculated:

$I_t / I_o = e^{-k\mathrm{GAI}}$

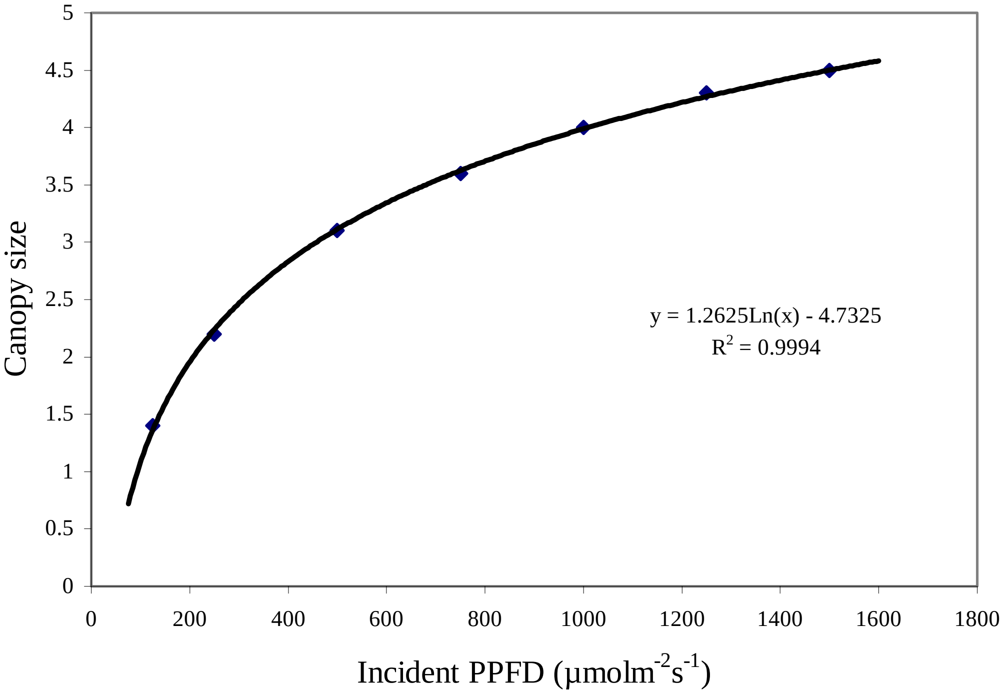
$\ln (I_t / I_o) = -k\ \mathrm{GAI}$

$\ln I_t - \ln I_o = -k\ \mathrm{GAI}$

$\mathrm{GAI} = (\ln I_o - \ln I_t)/k$

Our research (data not shown) has shown k to be quite variable across time (with crop development) and between crops. However, taking a value of 0.75 from the literature (Justes *et al.*, 2000) is sufficient for the purposes of this argument. The value of the light compensation point in oilseed rape canopies is not known, but a value of photosynthetic photon flux density (PPFD) of 40 µmol m^{-2} s^{-1} is reasonable (reference). With these figures, the size of canopy which would be above the light compensation point can be calculated for varying I_o. For example, at a PPFD of 1200 µmol m^{-2} s^{-1} this would be 4.53, at 600 µmol m^{-2} s^{-1} 3.6, at 300 µmol m^{-2} s^{-1} 2.68 and at 150 µmol m^{-2} s^{-1} 1.76. Plotting the ‘optimum’ canopy size against incident PPFD shows a logarithmic curve (Figure 15), indicating that in high light conditions quite large canopies could be sustainable, but in dull conditions large parts of such canopies would rapidly fall below the light compensation point. Incident PPFD varies sinusoidally throughout the day and across the season, so there is an obvious integral interaction between canopy size and incident sunlight. It is hoped that further consideration of this may explain more of the variance in the relationships described above, in publications to be appended to this report.

Figure 15: Canopy size giving a 40 µmol m^{-2} s^{-1} photosynthetic photon flux density at the base ('light' compensation point') with incident PPFD



4. Conclusion

The results presented above allow rationalisation of target canopy sizes for oilseed rape growth. As was found previously by Mendham *et al.* (1981) and Habekotté (1997), canopy sizes below a critical size before flowering (< LAI 1.75 or < GAI 3) could limit yield. After crops achieved this size, there was no relationship of crop size *per se* to yield across a large range of crop sizes (with leaf area index data). The GAI data indicated that very large canopy sizes could cause slight reductions in yield and an optimum pre-flowering target GAI was 3-4. Due to the extra cost of inputs (nitrogen, fungicide, plant growth regulators) required by larger crops and the lack of no significant yield benefit, there would seem to be no advantage in producing such large crops pre-flowering when crops of 3 - 4 units of GAI have the same range of yield potential.

The effects of pre-flowering canopy size on yield were largely explained by the relationship between pre-flowering canopy size and the subsequent numbers of fertile pods developed. The relationship was quadratic and the limitation to yield by small vegetative canopies was explained by their inability to produce over 6,000 pods m^{-2}, which even with relatively high numbers of seeds per pod, could cause limitation in yield. Maximum pod numbers were produced from canopies with LAIs of about 3.5 or GAIs of 5. However, a similar range of pod numbers was possible from GAIs of between 3 –5, with other factors than the vegetative size affecting pod number (presumably environmental conditions during flowering and pod set).

The optimum size of pod canopy for yield was about 7,500 pods m^{-2}. However, there was considerable plasticity in yield with a wide scatter of points in the region 5,000 – 10,000 pods m^{-2}. Canopies with GAIs in the region of 3-6 before flowering could produce this number of pods m^{-2}. The plasticity in yield was explained by the variation in seeds per pod with pod density. Although increased pod density was very strongly linearly correlated with decreased numbers of seeds per pod, in effect very similar yields were possible over a wide range of pod densities due to this compensation. At 7,500 pods m^{-2} about 15 seeds per pod were retained on average. As described in the first section, very similar pod canopy sizes could be derived from very different plant populations and vegetative canopy sizes, due to compensatory growth.

Thus, a reasonable target for canopy size of OSR crops would seem to be a GAI of 3 – 4 (with an LAI of more than 1.75) in April just prior to flowering. This canopy could be expected to develop in the region of 7,500 pods m^{-2} and achieve a GAI of 5 – 6 at full flowering. With an average retention of 15 seeds per pod then this crop could potentially produce 112,500 seeds m^{-2}. At a thousand seed weight of 4.5 g, this equates to a potential yield of 5.06 t ha^{-1}. At 8 seeds per pod, the potential yield would only be 2.88 t ha^{-1} but if 20 seeds per pod were retained on average, the yield potential would be 6.75 t ha^{-1}.

APPENDIX II: Effects of seed rate, sowing date and defoliation on canopy size and yield in oilseed rape.

1. Introduction

The potential to grow smaller canopies, with similar yields to conventional canopies, by varying agronomy was studied at ADAS Rosemaund from 1996-1999, although detailed growth analyses were done only in 1996-1997. The effect of halved seed rate, later sowing date and defoliation was studied.

2. Materials and Methods

Crops were grown and growth analyses were completed as described in Appendix I. Selected plots at Sutton Bonington (0 N plots 1996, 1998) were defoliated by hand with an Allen scythe in order to remove approximately 50% of the leaf area, but with the aim of leaving the growing points intact. However, in effect more than 50% of the leaf area was removed and some of the apices were also lost. At ADAS Rosemaund mowing of all sowing date x seed rate treatments was performed with an Allen scythe in February.

3. Results and Discussion

3.1. Effects of sowing date, seed rate and defoliation on yield and canopy size: ADAS Rosemaund 1996-1999

The effects on plant population and final seed yield of halving seed rate from 120 seeds m^{-2} to 60 seeds m^{-2} (or from about 6 kg ha^{-1} to 3 kg ha^{-1}), of delaying drilling from the end of August to the end of September, and of defoliation in January/February are summarised in Tables 1 (1996), 2 (1997) and 3 (1998 & 1999). The second level of each treatment was expected to produce smaller canopies than the first level in each case, although as described in section 3.1. of Appendix I, a large degree of compensatory growth was possible.

Table 1: Effects of sowing date, seed rate and defoliation on oilseed rape yields (1996)

Sown	**Seed rate (m^{-2})**	**Plant Population[a] (m^{-2})**	**Yield ($t\ ha^{-1}$)**	
			Not Defoliated	**Defoliated**
Early	120	114	4.03	4.35
(31/08/95)	60	65	4.37	4.46
Late	120	111	4.08	4.11
(25/09/95)	60	71	4.50	4.25

Sowing date x seed rate x defoliation (21 df)
SED = 0.329, LSD (5%) = 0.685, P = 0.954

Treatment means		Not Defoliated	Defoliated	Mean
Sowing date	Early	4.20	4.41	4.31
	Late	4.29	4.18	4.24
Seed rate	120	4.06	4.23	4.15
	60	4.44	4.36	4.40
Defoliation		4.25	4.30	4.28[b]

[a]Determined in March [b]Grand mean

No other significant main treatment effects

Table 2: Effects of sowing date, seed rate and defoliation on oilseed rape yields (1997)

Sown	**Seed rate (m^{-2})**	**Plant Population**[a]	**Yield ($t\ ha^{-1}$)**		**(m^{-2})**
			Not Defoliated	**Defoliated**	
Early	120	111	4.92	5.03	
(29/8/96)	60	58	5.17	5.34	
Late	120	95	4.76	4.61	
(24/09/96)	60	51	4.74	4.68	

Sowing date x seed rate x defoliation (21 df)
SED = 0.253, LSD (5%) = 0.526, P = 0.961

Treatment means	Not Defoliated	Defoliated	Mean
Early	5.05	5.19	5.12
Late	4.75	4.64	4.70
120	4.84	4.82	4.83
60	4.95	5.01	4.98
Defoliation	4.90	4.92	4.91[a]

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[a] Determined in March [b] Grand mean

Time of sowing (21 df)
SED = 0.126, LSD (5%) = 0.263, P = 0.003 (no other significant treatment effects or interactions)

Table 3: Effects of sowing date and seed rate on oilseed rape yields (1998 and 1999)

Sown	**Seed rate (m^{-2})**	**Plant Population[a] (m^{-2})**		**Yield ($t\ ha^{-1}$)**	
		1998	**1999**	**1998**	**1999**
Early	120	73	29	4.77	3.31
	60	44	20	4.67	2.89
Late	120	78	55	3.77	3.05
	60	55	33	4.05	2.82
Sowing date x seed rate					
df				55	68
P				0.136	0.386
SED				0.176	0.155
LSD				0.352	0.310

Treatment means		1998	1999
Sowing date	Early	4.72	3.10
	Late	3.91	2.94
	120	4.27	3.18
	60	4.36	2.86
Grand mean		4.32	2.99

[a] Determined in May

1998 time of sowing , P<0.001, SED (55 df) =0.12, LSD = 0.249

1999 seed rate, P = 0.004, SED (68 df) =0.110, LSD = 0.219

3.2.Effects of canopy management by reduced seed rate

Final seed yield was maintained or slightly improved by halving the seed rate, which produced slightly smaller canopies, in three out of the four trial years. This was across both normal (early September) and late drillings (delayed by approximately one month). There was a significant reduction in yield in the low seed rate in the year establishment was poorest, leading to sub-optimal plant populations. There was no significant effect ($P>0.05$) of lower seed rate on yield in 1996. The numerical difference between the seed rate treatment means was 0.25 t ha^{-1} (74% of the 5% LSD), with the lower seed rate producing the greater yield. Thus, similar or slightly improved yields could be achieved from the sparser populations resulting from lower seed rates. The plant number per m^2 in the low seed rate was higher than the theoretical number of seeds drilled per m^2. Thus establishment was successful, with uneven drilling, drilling at a slightly higher than anticipated rate of 60 seeds m^{-2} or contribution of volunteer rape plants (E. Williams, personal communication) accounting for the excess population. Population in the high seed rate did not exceed the number of seeds drilled and was about 175% of the ‘half seed rate’ sowing, although volunteer plants presumably may have contributed to this population also. Percentage establishment was slightly lower in the higher seed rate: 94% compared to 113% of seeds drilled in the low seed rate.

In 1997 the effect of seed rate was also non-significant ($P>0.05$) with the 0.15 t ha^{-1} mean yield advantage of the lower seed rate only 56% of the 5% LSD. Plant populations were broadly similar to 1996 (with the high seed rates giving 189% of the population in the low seed rates, on average). The populations were not greater than the number of seeds sown, indicating slightly poorer establishment (86% in the high seed rate and 91% in the low seed rate) and/or a lower volunteer population. So again, slightly enhanced or, at the least, maintained yields were obtained from halved seed rates with concomitant savings in seed costs of about £15 ha^{-1} (assuming a cost of £5 kg^{-1} for certified seed of Apex).

In 1998, the 0.09 t ha^{-1} benefit from the lower seed rate was not significant ($P>0.05$). In 1999, mean yield in the lower seed rate was significantly lower ($P<0.05$) than in the high seed rate treatment (0.32 t ha^{-1} on average, presumably due to the lower plant populations). Establishment was not as successful in 1998 and 1999 as in previous years and was less successful *pro rata* in the high seed rate than low seed rate sowings. In 1998, 63% of seeds in the high seed rate established on average, and 83% in the low seed rate. In 1999, percentage establishment was 35% in the high seed rate on average and 48% in the low seed rate. Again, in these two years very similar yields were produced from the halved seed rates, indicating little or no benefit from the high ‘insurance’ seed rates often considered necessary for rape. Indeed, in the poorest establishment year, the high seed rate did not produce significantly larger plant populations since percentage establishment was lower. If the high insurance seed rates do not produce better populations in years of poor establishment and yet cause excessive populations in years of good establishment, then there is little justification for using them. Over the four years of the trial and a range of establishment conditions, the 3 kg ha^{-1} seed rate gave an equivalent yield (0.03 t ha^{-1} benefit) to the 6 kg ha^{-1} seed rate with 50% of the seed costs and gave populations closer to the optimum needed for development of ideal pod numbers (see Appendix I). This can be explained because of the compensatory growth capacity of oilseed rape discussed section 3.1 of Appendix I, which means the lower seed rate crops exceeded the required critical pre-flowering canopy size in all years except 1999. The 3 kg ha^{-1} seed rate is therefore a good baseline for relatively good seed bed conditions. However, for poor seed beds with weed and pigeon pressure and for late sowings, a progressive increase in seed rate depending on the prevailing conditions may be more appropriate.

3.3 Effects of canopy management by sowing date

The yield of later-sown crops was maintained or slightly improved in two out of the four trial years and slightly reduced in two years (this was across the high and low seed rates). The data in Table 1 shows that in 1996 there was no significant effect ($P>0.05$) of sowing date on yield: yields were maintained whether the crop was sown at the beginning or at the end of September. There was also no effect on establishment, with very similar populations developed in both seed rate crops at the early and late sowing dates. The numerical difference (0.06 t ha^{-1}) between the early and late sowing date treatment means was only about 18% of the LSD required for statistical significance at the 5% level. Thus the earlier canopy closure and greater time for leaf development in the early sown crop gave no advantages for final yield. This agrees with previous research (Mendham, 1975, Shipway, 1981, Mendham *et al.*, 1981) where no yield advantage, or indeed a disadvantage, was often found for early sowings. This is because the yield is almost entirely dependent on the structure and photosynthesis of the pod canopy, which would appear to be more dependent on plant population, spring growth and the conditions during flowering and pod filling than on sowing date *per se*. As discussed in Appendix I, in the 1996 season the late-sown crops were able to reach the critical pre-flowering LAI of 1.75.

In 1997 (Table 2), there was a significant effect of sowing date ($P = 0.003$), with the overall mean yield 0.42 t ha^{-1} lower (156% of 5% LSD) in the late compared to the early sowing, presumably because the late-sown crops were below the critical size and the smaller pod canopy developed from crops was sub-optimal in this year whereas in 1996 it was closer to the optimum. However, the ‘early’ drilling date in September is relatively late compared with some commercial practice and delaying drilling still later lead to a relatively small (8%), though significant, difference: yields in 1997 were greater than in 1996 with even the lowest late-sown crop mean yield exceeding the highest yielding crop in 1996. This may indicate higher radiation levels during pod filling and hence a larger optimum canopy size, as discussed in Appendix I. Many rape crops are sown from as early as mid August when seed beds are dry which may cause problems with seedling death due to drying during emergence or development of secondary dormancy. The small effect of sowing date, allowing production of similar yields from much later sowings, would allow delaying of sowing until seedbed moisture was suitable for germination in such years without major yield penalties. Later sowing of rape may become even more feasible if springs continue to get warmer and earlier as they have over the past 20 years. As in 1996, there was no discernible effect of sowing date on final establishment, with similar populations developed at both sowing dates in both seed rates.

In 1998, on average there was also a significant decrease (0.81 t ha^{-1}, 142 % of 5% LSD) in the late sowing date crops compared to the mean yield in the early sowing date, although again the plant populations were not significantly different. The difference in 1999 (0.16 t ha^{-1}, 73% of 5% LSD) was not significant and in this year, all yields were low. Establishment was also poorer, with slightly fewer plants contributing to yield in the early sowing date compared to the late sowing date.

Over all, delaying sowing for a month from the beginning of September led to no significant yield penalty (two years out of four), or relatively small significant decreases in yield (0.36 t ha^{-1} on average). Later sowing date is probably currently not the most practical option for canopy management, as many producers wish to get their rape drilled and ‘out of the way’ to concentrate on cereal drilling. It would also appear to be a more risky strategy than lowering seed rate due to the small decreases in yield in some years. This is probably due to interaction of plant size with growth conditions in the spring and during flowering and pod filling, which cannot be predicted reliably at time of sowing, meaning that some of the late-sown crops were unable to reach the critical pre-flowering size needed for development of optimum yield. However, the evidence is that there could be little benefit to the ever earlier sowing dates (early-mid August) prevailing in recent years as these crops would far exceed the critical pre-flowering size. Early September probably remains the optimal date. Indeed, as there is little penalty from late sowing, there may be benefits in waiting for more optimal seed bed conditions to allow better establishment. For example, there was slightly better establishment from the later sowing date in 1999. However, such decisions depend strongly on local field conditions and the attitude to risk taken by the farmer.

3.4. Effects of canopy management by defoliation

The overall effect of defoliation in 1996 was not significant (P>0.05), with the mean difference of 0.05 t ha^{-1} only 15% of the 5% LSD (this was over the two sowing dates and two seed rates used). However, the effect of defoliation appeared to be greater in the larger crops (*i.e.* early sown and high seed rate) where the numerical difference in yield (greater in the defoliated crop) approached 50% of the LSD; there was little appreciable effect on yield of defoliating late sown and low seed rate crops. The overall effect of defoliation (0.02 t ha^{-1}) in 1997 was also non-significant (P>0.05), with similar yields from defoliated crops in most cases. This is in contrast to previous work (Spink, 1992) where larger benefits of mowing were found. In this year, the largest yield differences again came from defoliating the larger early sown crops, whereas the late-sown crops showed no discernible yield benefit. No further defoliation studies were carried out at ADAS Rosemaund after 1997. Also, no growth analyses of defoliated crops were undertaken at Rosemaund to compare the effects on subsequent canopy development, although plots defoliated at Sutton Bonington in 1998 had consistently less leaf and stem (measured by green area index and dry matter accumulation, data not shown) throughout the season and remained upright, whilst control plots lodged (Stubbings, 1998). There was also a yield benefit of 0.33 - 0.51 t ha^{-1} from defoliation at SB (Table 4. Yield benefits of similar magnitude have been found with other defoliation studies (Spink, 1992). The smaller benefits in the Rosemaund studies in 1996 and 1997 might be because the canopies were not excessively large to start with.

Table 4: Effects of defoliation on yield at Sutton Bonington, 1998 (Stubbings, 1998)

Nitrogen Application (kg ha^{-1})	**Yield (t ha^{-1} @ 91% dm)**	
	Not defoliated	**Defoliated**
100	3.04	3.55
200	3.29	3.62

3.5. Effects of growth season

Comparison of the grand means for all the experiments (Table 5) showed that season had the biggest impact on yield ($P<0.001$). There was a difference of 1.92 t ha^{-1} in the grand mean yield between the best (1997) and worst years (1999). The greatest difference caused by the sowing date x seed rate x defoliation experiments was 1 t ha^{-1} (between early and late-sown high seed rate crops in 1998) and the differences caused by these treatments were more usually 0.25 – 0.5 t ha^{-1} or less.

This large variation in yield with season can probably be explained by a variation of about +/- 25% in incident radiation in dull and bright years compared to average years, as described in Appendix I; in bright years large canopies would be able to utilise the light more effectively and yield more than a canopy which would be optimal in an average year. In dull years, even an average-sized canopy would be too large with shading of lower pods and a smaller canopy (which would be too small in average and bright years) would give optimum yield. The true optimum canopy size for oilseed rape depends on the long term variation in solar radiation.

Table 5: Grand (season) mean yields for experiments at ADAS Rosemaund, 1998-1999

Year	1996	1997	1998	1999
Grand mean yield (t ha^{-1})	4.28	4.91	4.29	2.99

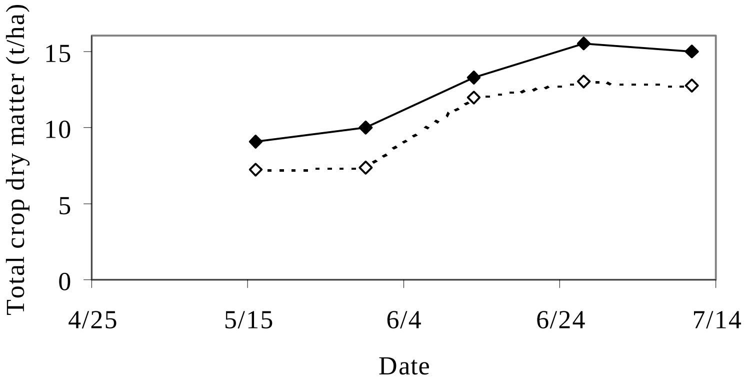
3.6. Effects of canopy management strategies on canopy size

3.6.1. 1996 growth analysis

Growth analysis in 1996 compared early-sow high seed rate (E120) with late-sown low seed rate L60 crops (Table 1), which were assumed to be the ‘extremes’ of canopy size. In actual fact, due to the compensatory growth discussed in Appendix I, the canopies were very similar and demonstration of statistically significant differences between them was difficult.

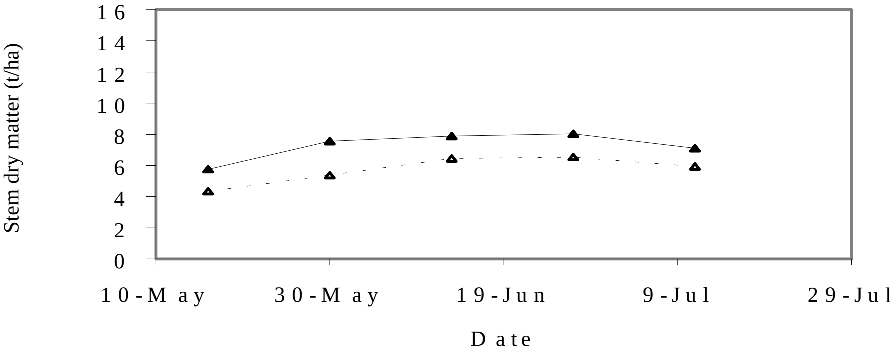
The data in Table 1 shows that in 1996 there was no significant effect on yield of halving seed rate from 120 seeds m^{-2} (a reduction in seed rate from 5.4 kg ha^{-1} to 2.7 kg ha^{-1}, assuming a mean seed weight of 4.5 mg). In fact yields were numerically (although not significantly) greater from the lower seed rate sowings. There was also no significant effect of later sowing-date, but with numerically greater yields from sowing at the end of September compared to the end of August. It is therefore unsurprising that the differences in total crop canopy size between the ‘dense’ L120 and ‘sparse’ E60 crops were relatively small. However, due to the significantly greater number of plants surviving to contribute to yield in the high seed rate crops (Table 1, although the double seed rate did not quite produce double the number of plants), the canopies were composed of plants of radically different structure. The dense crop had significantly ($P<0.001$) greater dry matter accumulation (Figure 1) throughout development.

Figure 1: Total dry matter production of E120 (unbroken line) and L60 crops (broken line), ADAS Rosemaund 1996



Throughout growth, the total dry matter was consistently about 2 t ha^{-1} greater in the dense E120 crop than in the sparser L60 crop. At final harvest, the dry matter in the E120 crop (~15 t ha^{-1}) was 115% of the L60 crop (~13 t ha^{-1}). However, the E120 population was 160% of the L60 population. This shows that the L60 canopy was of a radically different structure to the E120 canopy, consisting of fewer plants of greater dry mass per plant (20 g dm plant^{-1} compared to 13.5 g dm plant^{-1}). This difference was mostly accounted for by significantly ($P<0.05$) greater stem dry matter (Figure 2) in the E120 crop. Thus the pod canopy in the late, low-seed rate crop was supported by fewer but thicker stems.

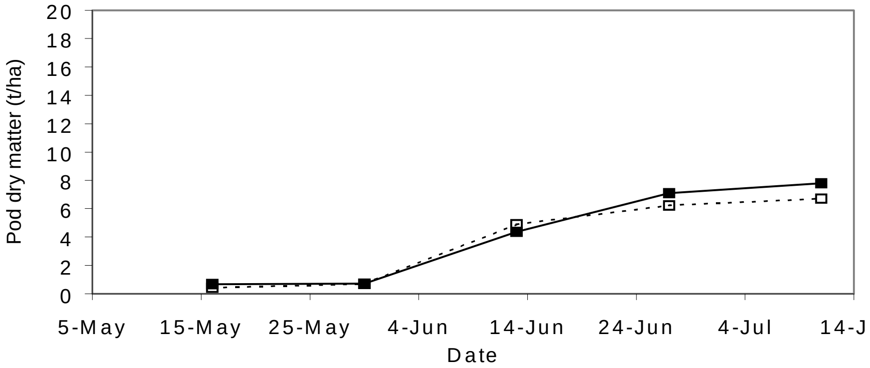
Figure 2: Total stem dry matter (t ha^{-1}) in E120 and L60 crops.



There was only a small non-significant ($P>0.05$) difference in pod dry matter towards the end of crop growth (Figure 3), with very slightly greater pod dry matter in the E120 crop than the L60 crop. This was due to greater amounts of pod wall material in the E120 crop, as it eventually yielded less than the L60 crop.

There was no significant difference in the leaf dry matter (data not shown), which senesced rapidly during the pod filling phase after flowering.

Figure 3: Pod dry matter (t ha^{-1}) in E120 and L60 crops



The green area index (GAI) measurements showed similar trends. Total GAI was consistently about 1 unit greater in the E120 compared to the L60 crop (Figure 4), although due to variation between the replicate plots this was not significant at the 5% level. The maximum GAI (mid-flowering) at 7 units for the E120 and 4.5 units for the L60 were relatively small compared to some commercial crops where the GAI may be above 8 or 9 at full flowering.

Figure 4: Green area index of E120 and L60 crops.

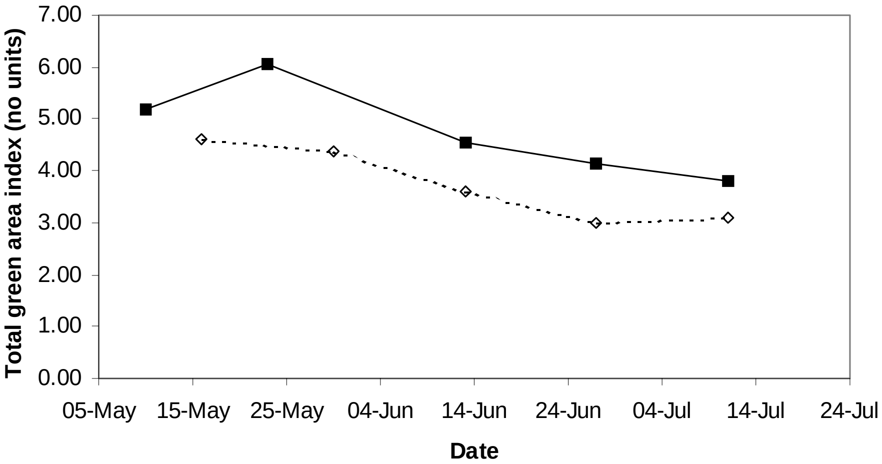


Figure 5: Stem GAI of E120 and L60 crops

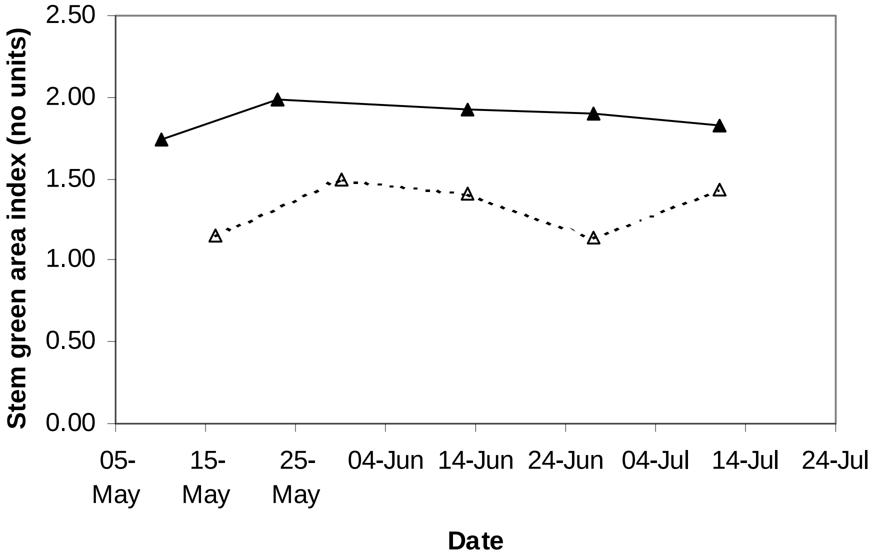
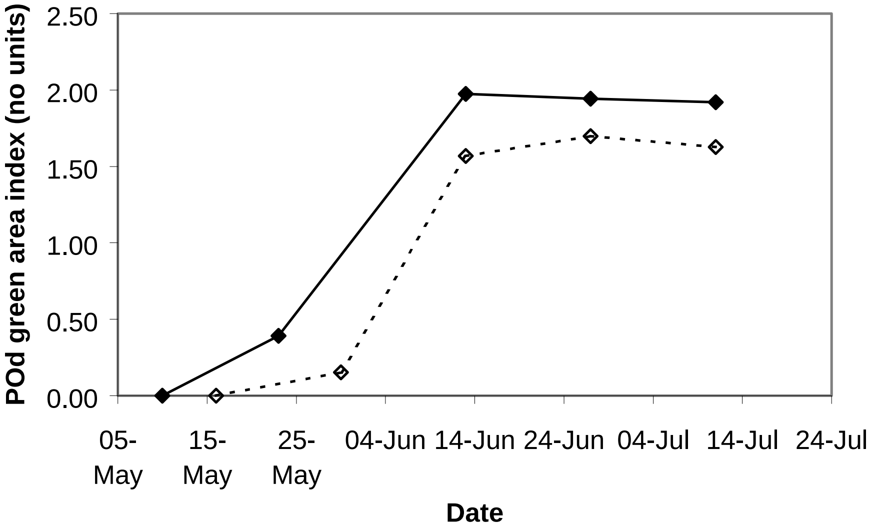


Figure 6: Pod GAI of E120 and L60 crops



This difference in GAI was explained by a consistent significant ($P<0.05$) difference of about 0.75 units of GAI in stem (Figure 5) and a non-significant ($P>0.05$) difference of about 0.25 units in pod GAI throughout development (Figure 6), with the E120 crop having the greater green area. Yield of the L60 crop was 4.50 t ha^{-1} compared to 4.03 t ha^{-1} in the E120 crop. Light interception measurements showed that a greater fraction of the incident light penetrated to the bottom half of the pod layer in the sparser L60 crop than in the denser E120 crop throughout development.

The above analysis shows that despite the extremes of canopy management – with halving of seed rate and delaying of sowing by one month – that quite similarly-sized canopies were produced (about 4.5 and 3.5 units of GAI during pod fill for the E120 and L60 crops respectively, producing 15 and 13 t ha^{-1} dry matter respectively). Due to the overall similarity and considerable inter-plot variation (generating large LSDs) it is therefore very difficult to demonstrate significant differences between treatments in the growth analysis (particularly with the individual components). However, this analysis demonstrates the large compensatory growth capacity of oilseed rape as discussed in Appendix I – with the smaller number of plants in the L60 crop producing more leaf, stem and pod per plant than the plants in the E120 crop. Due to the thicker stems produced by plants in the lower populations, the pod canopies remained more upright allowing penetration of the light to the basal pods whereas lodging of the thin-stemmed plants in the high density crop caused compression of the pods into a dense layer through which there was poor light penetration. Also, the sparser pod canopy in the L60 crop allowed more light to penetrate to the basal pods and due to the slightly reduced number of pods m^{-2} there was more light available per pod (data not shown).

3.6.2. 1997 growth analysis

In 1997, detailed growth analysis compared the E120 and L120 crops. Although there were large significant differences between the early growth stages, during the pod filling phase of relevance to yield the crop canopies were not significantly different in size (data not presented). There was no significant difference in the proportion of light penetrating to the lower 50% of pods (data not shown) and the final yields (4.92 and 4.76 t ha^{-1}) were not significantly different. This data again demonstrates the capacity of smaller canopies of different structure to produce pod canopies and yields similar to more ‘forward’ or ‘lush’ crops.

3.6.3.1998 and 1999

Fewer detailed growth analysis was carried out in 1997-1999 as analyses concentrated on assessment of the effects of canopy management on pest and disease pressure. However, as described in Appendix IV, due to compensatory growth the ‘extreme’ canopy sizes were actually very similar during the pod filling phase.

4. Conclusion

The results described above show that seed rate, sowing data and defoliation can be used as tools to manage oilseed rape canopies and produce canopy sizes closer to the desired GAI of ~ 3 before flowering (which will produce a GAI of ~ 5 in mid-flowering, returning to a GAI of about 3 in pod filling). Due to compensatory growth, canopies produced from crops sown at lower seed rates were quite similar in size to those at high seed rates, although composed of plants with thicker stems producing more pods per plant. These crops usually lead to higher yields and better harvest index. Similarly, smaller later-sown crops could also produce similar pod canopies to the larger earlier crops, although late sowing date was not as consistent as halving seed rate resulting in small yield penalties in half of the assessments. This was because of failure of the crop to reach the critical pre-flowering size due to the spring conditions following late drilling. As these conditions cannot be predicted at the time of sowing, sowing date decisions should be dependent on autumn conditions and workload. Mowing did not result in significant yield benefits, but this was probably because none of the crops grown at Rosemaund were particularly large.

APPENDIX III: Effects of nitrogen fertilisation on canopy size, yield and margin over nitrogen cost.

1. Introduction

The effects of timing and rate of nitrogen fertilisation on yield and on the gross margin (over nitrogen costs) were studied at Sutton Bonington from 1998-1999. The nitrogen timings are shown in Appendix I (Table 2) where the soil mineral nitrogen determinations were also recorded and the split between early and late application is shown in Table 1 of this Appendix.

2. Materials and methods

Agronomic treatments were as previously described and growth analyses were completed as described in Appendix I.

3. Results and Discussion

3.1. Effects nitrogen fertilisation rate on yield

The yields of all the treatments in the experimental programme on nitrogen (adjusted to 91% dry matter) are summarised in Table 1. The lowest yield was 3.32 t ha^{-1} from a zero fertilised treatment in 1999 (soil mineral nitrogen = 76 kg ha^{-1} in February). The highest yield of 5.63 t ha^{-1} was achieved in 1997 with a crop fertilised with 160 kg ha^{-1} N (in addition to soil mineral N reserves of 49 kg ha^{-1} in February). The experiments fell into two groups: in 1996 and 1998 there was no significant yield response to nitrogen after analysis of variance (P(1996)>0.05, P(1998)>0.5). This was the case both on ANOVA of the whole data set and when the individual response series were analysed separately, except for a significant ($P<0.001$) reduction of yield with increased application of N split equally between early and late applications in 1996. Indeed, in 1996 the highest yield of 4.8 t ha^{-1} came from a treatment that received zero nitrogen. In 1997 and 1998, the N fertilisation effect was significant ($P<0.001$) and showed the classic nitrogen response curve, with small initial applications causing large yield responses, with ever larger applications producing only small (or no) benefits in yield.

Table 1: Yields of nitrogen response experiments at Sutton Bonington, 1996-1999

Year	1996		1997		1998		1999
N regime[a]	Yield (t/ha)	N regime[a]	Yield (t/ha)	N regime[a]	Yield (t/ha)	N regime[a]	Yield (t/ha)
0	4.80	0	4.04	0	3.48	0/0	3.32
50/50	4.63	50	4.87	50/50	3.77	50/50	4.10
100/100	4.36	100	5.20	100/100	3.71	100/100	4.08
0 (defoliated)	4.30	200	5.42	150/150	3.65	150/150	4.10
50/0	4.68	300	5.47	200/200	3.75	200/200	4.06
100/0	4.42	40*/200	5.34	0	3.52	0/50	4.29
150/0	4.59	0*/200	5.61	0/80	3.89	100/100	4.32
200/0	4.52	40*/160	5.23	0/160	3.61	150/150	4.69
250/0	4.30	0*/160	5.36	50/0	3.68	200/200	4.50
0/50	4.76	80	5.20	50/80	3.56		
0/100	4.68	80	5.28	50/160	3.76		
0/150	4.49	160	5.46	100/0	3.88		
0/200	4.57	160	5.63	100/80	3.68		
0/250	4.78	0	3.78	100/160	3.64		
SED	0.179		0.194		0.198		0.210
DF	24		42		39		24
LSD	0.369		0.388		0.400		0.430
P	0.097		<0.001		0.682		<0.001
Subsidiary experiments[b]							
		0	3.62			0	3.65
		50	4.30			80	4.35
		100	4.63			100/100	4.24
		200	4.62			100/60	4.07
		300	4.60			40/40	3.69
		400	4.33				
SED			0.180				0.251
DF			14				11
LSD			0.385				0.553
P			<0.001				0.057

[a] First figure shows first (early March) application, second figure shows late (late march or April) application.

[b] In 1997, subsidiary experiment was N response in a high plant population area (main trial at low plant population); in 1999 various ‘canopy management’ strategies were tested.

*First figure shows the seed bed nitrogen added the previous autumn

In many cases the effects were not significant at the 5% level in analysis of variance because of the high degree of inter-plot variation in oilseed rape yield. This caused large values for the least significant differences at 5% (0.37-0.55 t ha^{-1}). The responses in 1996, 1997, 1998 and 1999 are shown in Figures 1, 2, 3 and 4 respectively. The few significant differences were between zero fertilised and fertilised plots (1997, 1999) where yield increases of about 0.8 t ha^{-1} were possible from relatively moderate (50 – 100 kg ha^{-1}) applications of nitrogen, following the classic form of the traditional nitrogen response.

Figure 1: Effect of N fertilisation on yield, Sutton Boningon 1996 (Diamonds = split equally (1 March/25 March), squares = all applied early, triangles = all applied late)

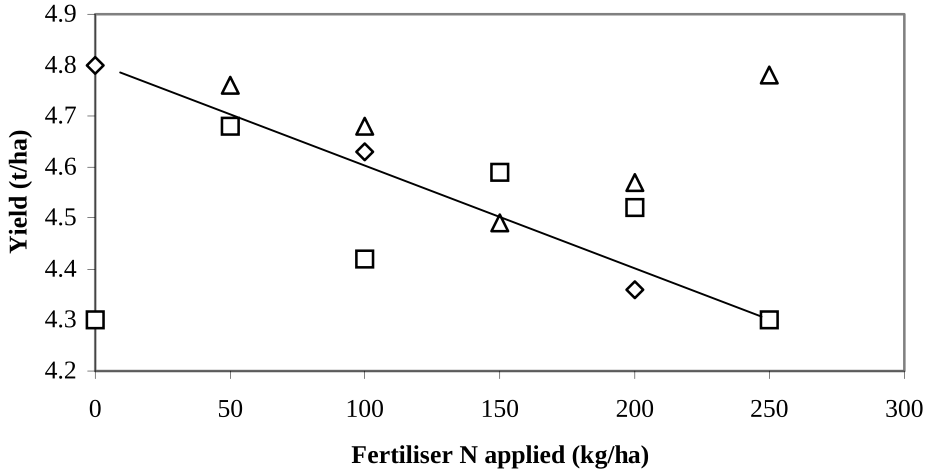


Figure 2: Effect of N fertilisation on yield, Sutton Bonington 1997 (LPP = low plant population, HPP = high plant population)

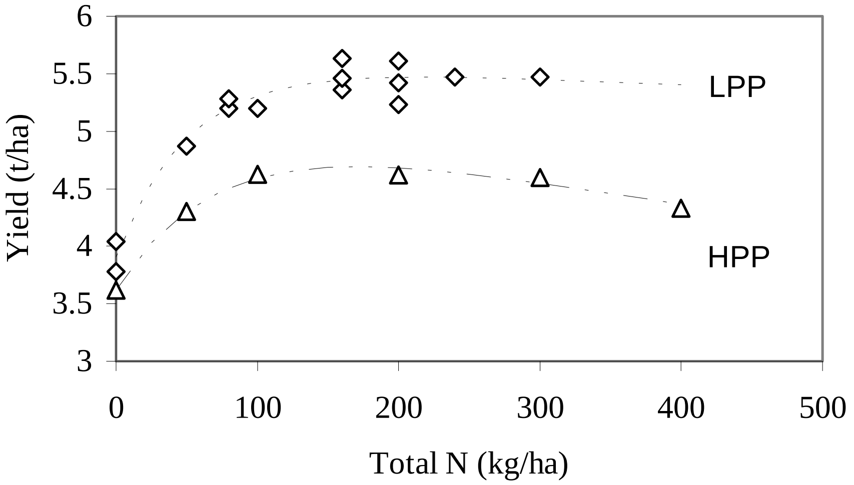


Figure 3: Effect of N fertilisation on yield, Sutton Bonington 1998

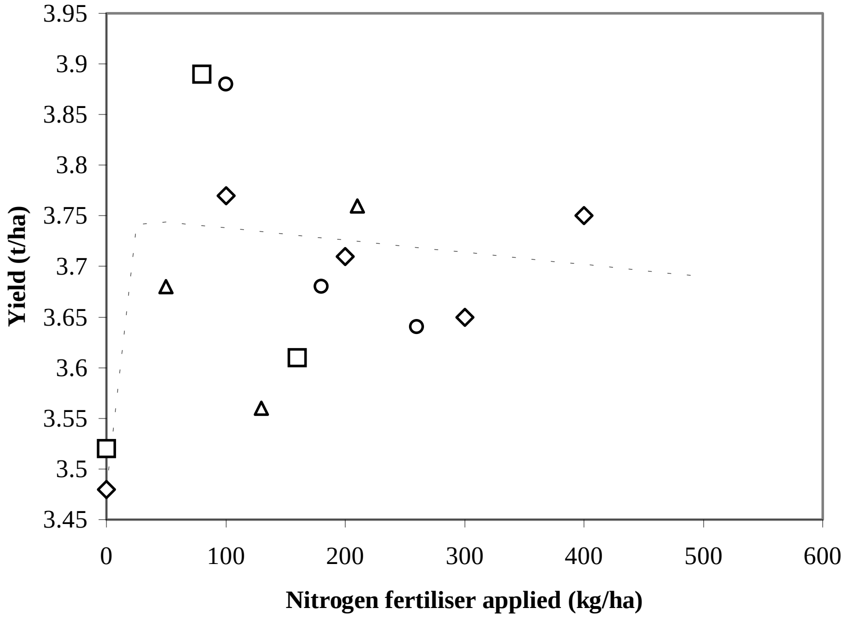
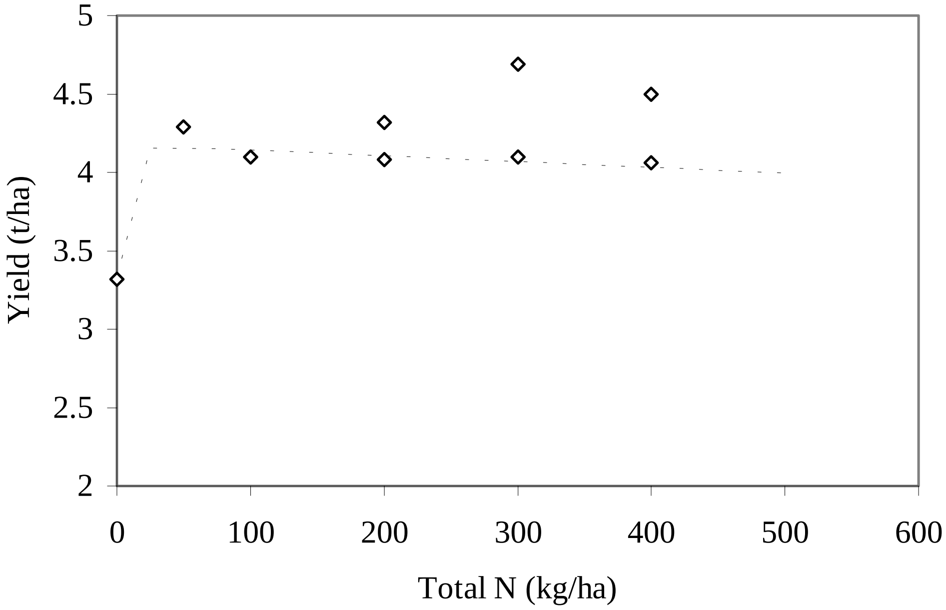


Figure 4: Effect of N fertilisation on yield, Sutton Bonington 1999



In 1996, there was no overall significant effect of nitrogen fertilisation (Figure 1) at the 5% level, because the late 250 kg ha^{-1} N application gave a high yield comparable to the zero N application (~4.8 t ha^{-1}). However, effects were significant at the 10% level ($P = 0.097$). Recognising the downward trend with increasing N fertilisation in the data for the early nitrogen response and the early/late split applications, a significant ($P<0.001$) linear regression could be fitted to explain the reduction in yield by excess N application to these data if the late nitrogen application response was omitted. The zero N defoliated treatment (shown on Figure 1 by the filled square) was also excluded, giving an equation (Yield = 4.76 –

0.0017*N), explaining about 75% of the variance. In 1996, the downward trend in yield can be attributed to the high SMN levels (165 kg ha^{-1} in February), which provided enough N for crop growth without additional applications. The higher levels of N available in the fertilised plots led to excessive canopy development and decreased yield via the mechanisms described in the preceding section.

The response to nitrogen fertilisation in 1997 followed the classic linear plus exponential curve. In this year, due to differences in establishment in the farm crop used for the experiment, the nitrogen response was studied in areas of low and high plant population (subsidiary experiment). The low plant populations yielded 0.5 – 1.0 t ha^{-1} better than the high plant populations (Figure 2) emphasising the benefits of smaller canopies. In zero fertilised plots of the low plant population, yields were about 3.9 t ha^{-1} and application of 150 kg ha^{-1} N increased yields to about 5.4 t ha^{-1}. The yield response could be explained by a significant ($P<0.001$) linear plus exponential curve, accounting for 94% of the variance (yield = 5.61 – 1.698*(0.981)^{N} – 0.005*N). Additional increases in nitrogen application above 150 kg ha^{-1} produced no further change in yield. In the high plant population plots, control yields were similar (3.6 t ha^{-1}), but 150 kg ha^{-1} N only increased yield to 4.6 t ha^{-1}. Again a significant ($P<0.001$) linear plus exponential curve explained the relationship, accounting for 97% of the variance (yield = 5.17 – 1.552*(0.986)^{N} – 0.002*N). Not only were the high population plots less yield-responsive to N than the low population plots, but the deleterious effect of over-fertilisation was more marked, with a trend for decreased yield with excessive N application.

In 1998, the response to nitrogen fertilisation was not significant, as in 1996 (Figure 3). Control (zero fertilised) yields of about 3.6 t ha^{-1} were increased to 3.9 t ha^{-1} by 80 kg ha^{-1} N, but this was not significant (5% LSD = 0.4 t ha^{-1}). The linear plus exponential function which explained the response in 1997 was not significant ($P = 0.467$) and the curve shown on Figure 3 (yield = 3.75 – 0.27*(0.856)^{N} – 0.00012*N) explained only 44% of the variance in the data. No better responses were fitted by using only the 0-400 kg ha^{-1} split nitrogen response or the data assessing the effects of increasing early applications of N, since there were too few data points. These responses were also not significant when analysed individually by ANOVA. The reason for a lack of response to nitrogen in 1998 is difficult to explain, since a strong response would be expected due to the low SMN levels recorded in February (44 kg ha^{-1} N). One explanation might be that 1998 was an unusually dull year (Stokes, personal communication) so that even the small canopies with limited N supply were sufficient to intercept the radiation, with no benefit from larger canopies (see Figure 15 of Appendix I).

In 1999, a classic response was again observed (Figure 4). Control yields of about 3.4 t ha^{-1} were increased to 4.4 t ha^{-1} by application of 50 kg ha^{-1} N. However, yield was not significantly increased by larger N applications. The fitted curve (yield = 4.18 – 0.85*(02.852)^{N} – 0.00037*N) was only significant at the 10%

level (P = 0.091) and accounted for 52% of the variance. In 1999, soil mineral nitrogen levels were intermediate (76 kg N ha^{-1}) between the 1997, 1999 and 1996 levels.

The data show the importance of knowledge of soil fertility in assessing nitrogen fertilisation requirements. In the year when SMN in February was high (> 150 kg ha^{-1}), additional nitrogen application had a deleterious effect on yield through development of an excessive canopy size and this was also the case in the dull year 1998 when large canopies were not needed. However, in the years when SMN was low, application of 80-150 kg ha^{-1} N boosted yield by over 1 t ha^{-1}.

3.2. Effects of nitrogen fertilisation on canopy size and yield

Detailed growth analyses were completed on 0, 100 and 200 kg N ha^{-1} fertilised crops at Sutton Bonington in 1996 and 1998, and on 0, 100 and 300 N fertilised crops 1997. Yield analysis only was completed in 1999.

3.2.1. 1996 Growth analysis

The effects of N fertilisation on canopy size at SB in 1996 were smaller than hypothesized. Although 0, 100 and 200 N crops were studied in detail, only the data for the 0 and 200 N crops is presented. Before fertilisation in the spring there was no significant difference in canopy size. After the end of May, total GAI in the 200N crop was 0.34-1.43 units of GAI greater than in the 0N crop, although this difference was only statistically significant at the final sample point (Figure 5). Both canopies were larger throughout most of pod filling compared to the 3 units of GAI required for full light interception. Analysis of the leaf, stem and pod fractions showed numerically greater (but not statistically significant) stem and leaf GAIs in the 200N compared to the 0N crop (data not shown). There were no differences in pod GAI (Figure 6) until the pre-harvest sample. Pod GAI in both the crops was around 3 throughout pod filling, meaning that with the area also contributed by stems there would be little light penetrating to the basal pods.

Figure 5: Total green area index with time (SB 1996) showing effects of N fertilisation. Solid line and circles, 200 kg/ha N. Broken line and open circles nil N.

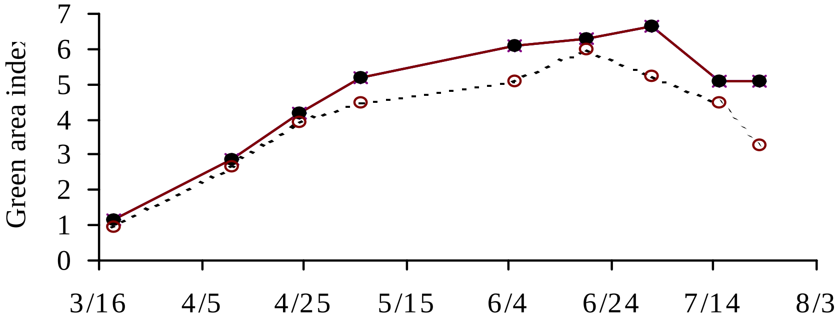
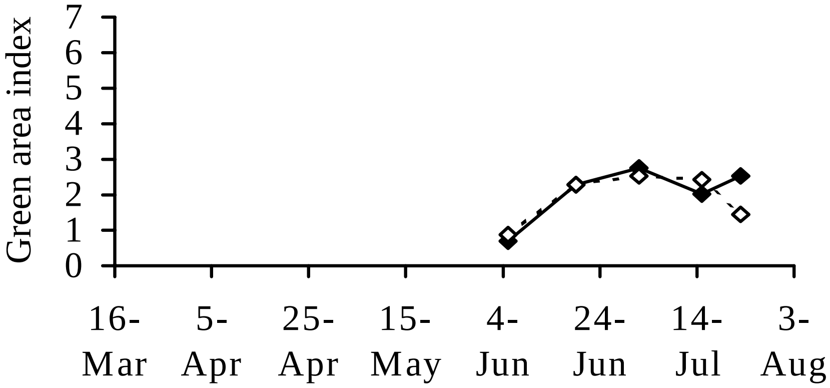


Figure 6: Total green area index of pods with time (SB 1996) showing effects of N fertilisation. Solid line and circles, 200 kg/ha N. Broken line and open circles nil N.



Analysis of crop total dry weight also showed smaller than expected differences. There were no significant differences between dry matter accumulation in the 200N and 0N crops until July, when growth analysis showed a smaller amount of dry matter in the pod of the 0N crop (data not shown). This was probably due to sampling variation, but could be explained by a higher harvest index in the 0N crop, with larger numbers of seed contributing to yield for a smaller dry mass of pod. Analysis of pod numbers and seeds per pod showed greater numbers of pods per square metre in the 200 N fertilised crop compared to the 0 N crop. However, there were slightly greater numbers of seeds per pod in the 0 N crop.

The 1996 growth analysis shows the difficulty in demonstrating significant differences to explain the yield variation between even the most extreme treatments in any particular year due to the limited number of crops. Therefore, rather than compare the crops grown in 1997 and 1998 the data was pooled and is discussed below.

3.2.2. Effects of N fertilisation on crop size and pod numbers

The comparison in section 3.2.1 shows the difficulty in assessing N treatment effects on growth when only a few crops were available for comparison in each year. Therefore, the effect of N fertilisation on the LAI and GAI before and during flowering and the subsequent pod density (some of the critical canopy parameters identified in Appendix I) will be discussed in this section. The regressions relating canopy size parameters to applied N gave poor fits as the wide variation in soil mineral nitrogen was not accounted for. Therefore, a crude estimate of total soil nitrogen supply (SNS). Previously it has been shown that for zero-fertilised wheat crops, February SMN levels in the top 90 cm soil give a good indication of the amount of N in the crop at harvest (Stokes *et al.*, 1997). Consequently, soil nitrogen supply (SNS) has been estimated as 100% February SMN + 60% of applied fertiliser (Stokes *et al.*, 1997), as fertiliser N is taken up of an average efficiency of 60% (range 40-90%). However, recently it has been shown that for wheat, nitrogen uptake continues throughout development so that only 60% of February SMN is available for canopy expansion (Sylvester-Bradley, personal communication). Therefore, for these calculations, SNS for canopy expansion was assumed to be 60% of February SMN plus 60% of applied N. The effect of N on LAI before flowering is shown in Figure 7. A significant ($P<0.001$) linear plus exponential regression relationship ($LAI = 2.37 - 2.78*(0.984)^N + 0.0064*N$) accounted for about 72% of the variance, and leaf area index increased with increased N supply. Each unit of LAI required a supply of about 35-50 kg ha^{-1} N (with more N required for a unit of LAI at higher LAIs).

Figure 7: Effect of nitrogen supply on leaf area index before flowering

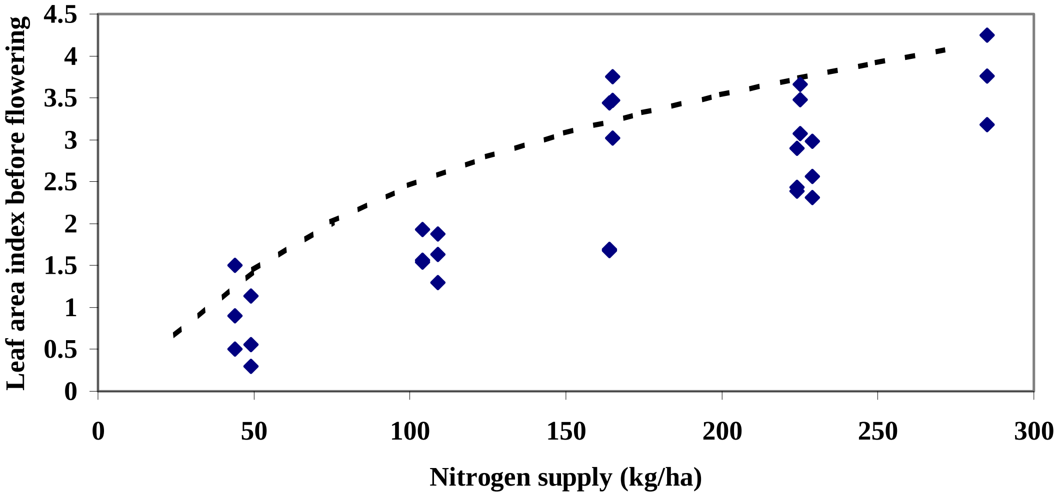
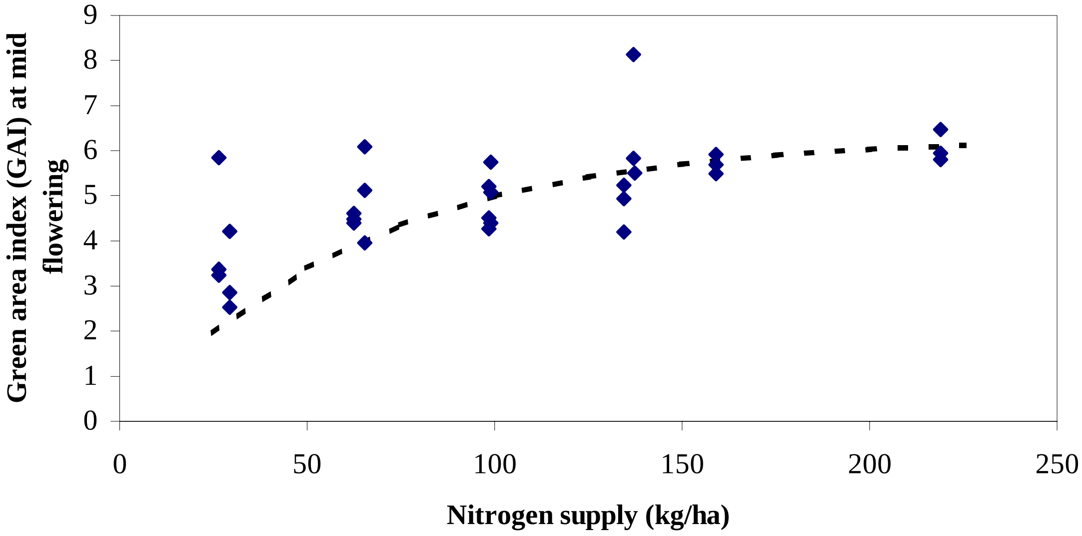


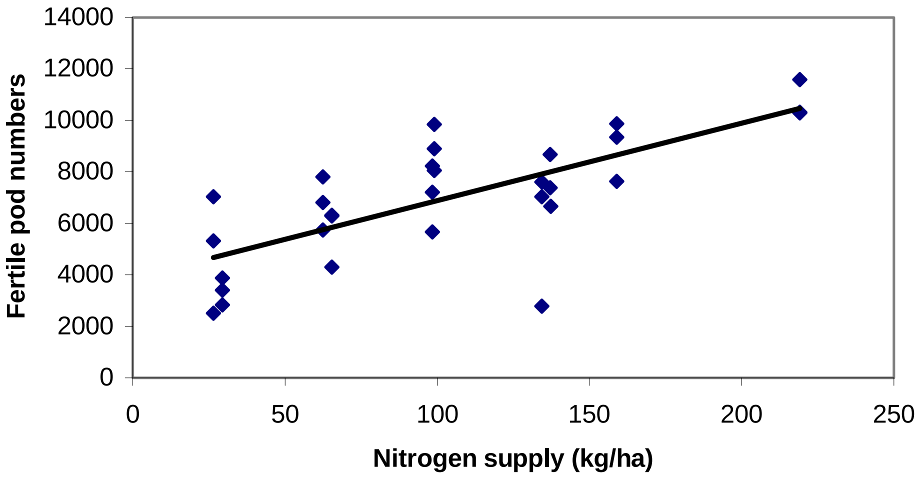
Figure 8: Effect of N supply on green area index at mid-flowering



Therefore, to reach the critical crop size of 1.75 LAI before flowering Appendix I), a supply of about 63 kg ha^{-1} N was required. In many of the crops studied in this project, 60% of February SMN was sufficient to provide for this adequate crop growth (e.g. 1996, 99 kg ha^{-1}), although in some cases small N applications in February/March were required to reach the critical size. However, very large early supplies of N lead to over-production of leaf, which Appendix I showed does not benefit yield. A similar relationship was observed between GAI before flowering and N supply (GAI = 6.28 – 6.47*(0.984)^{N} - 0.0077*N, P<0.001 accounting for 64% of the variance: data not shown). Unlike the LAI/N supply relationship, the curve for

GAI/N supply approached the asymptote at an N supply of about 150 kg ha^{-1} N, so greater supplies of N did not increase pre-flowering GAI above about 5-6 units. The relationship of N supply to GAI at mid-flowering was very similar (Figure 8), such that large N supplies resulted in large canopies during flowering and mutual shading. Again, a significant ($P<0.001$) linear plus exponential regression was fitted ($GAI = 5.7 – 2.8*(0.988)^N +0.0029*N$) 3.4) although less of the variance (38%) was accounted for than for the N supply/pre-flowering GAI relationships. The N supply also significantly affected the fertile pod numbers developed after flowering; the numbers of pods increased linearly as nitrogen supply increased (Figure 9). The fitted equation Pods m^{-2} = 30.2*N + 3869 was significant ($P<0.001$) and accounted for about 52% of the variance. To generate the optimum pod numbers of 6 – 8,000 identified in Appendix I, a this relationship showed that a supply of about 71 - 137 kg ha^{-1} N was needed, *i.e.* approximately 10 - 75 kg ha^{-1} N in addition to the amount needed to generate the critical pre-flowering LAI.

Figure 9: Effect of nitrogen supply on number of fertile pods

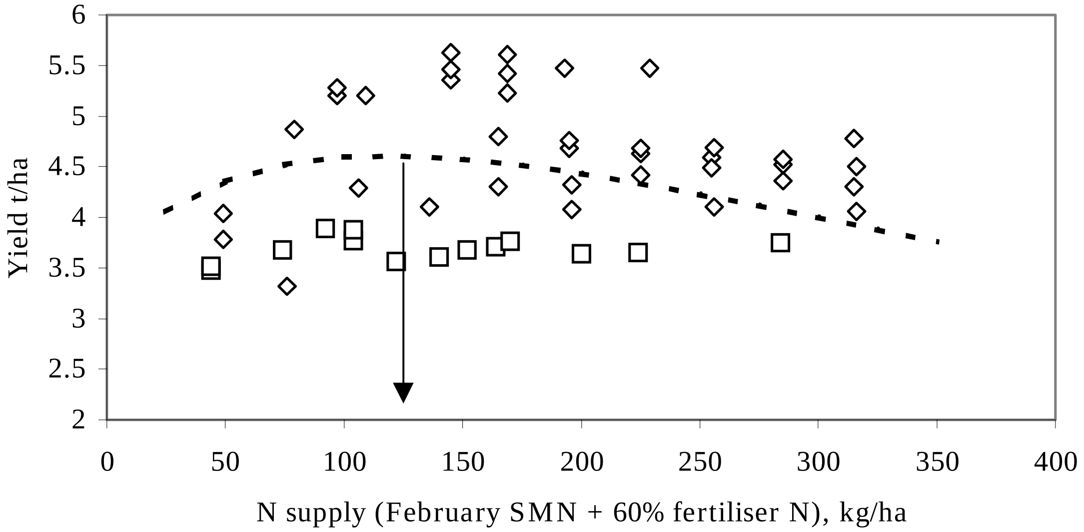


However, formation of optimum pod numbers was also possible at much lower nitrogen supplies. However, the data shows that about 6,000 pods could easily be produced from SMNs of around 120 kg ha^{-1} in February. This was seen in 1996 where enough SMN to develop the correct crop structure was available and additional N fertilisation was deleterious. However, in situations where there was less SMN, augmentation with fertiliser N was necessary (e.g. 1997). However, as well as providing sufficient N to develop the vegetative canopy and pods, some would also be required for deposition in the seed; this could be provided by retranslocation from senescing leaves and by continued uptake from the soil.

3.2.3. Effects of nitrogen supply on yield

Using the standard assumptions for calculation nitrogen supply (Stokes *et al.*, 1997) the nitrogen supply for the various crops can be calculated, assuming that all SMN in the top 90 cm of the soil is available to the crop (*i.e.* uptake continues after the approximately 60% of SMN required for canopy expansion is taken up) and that 60% of the applied fertiliser is recovered. This latter value is an average of a large range (40-90%) and thus may explain some of the variation in the data. For this calculation, the total SMN in February was used as it was assumed that uptake would continue during pod filling and contribute Using the N supply figures thus calculated, the effect of nitrogen supply on crop yield can be plotted (Figure 10) allowing assessment of the optimum N supply for the greatest yields. Although there was a broad range of data, a significant ($P = 0.031$) linear plus exponential curve could be fitted to explain about 12% of the variance. The data from 1998 were excluded from the analysis as they formed a distinct set (shown by the open squares on the figure) which did not fit the general relationship. The equation of this relationship was $\text{Yield} = 5.67 - 2.90*(0.985)^N - 0.00508*N$.

Figure 10: Optimum nitrogen supply for oilseed rape yields (Sutton Bonington 1996-1999)



Yields were limited by soil nitrogen supplies < 100 kg ha^{-1} (too few pods) or > 170 kg ha^{-1} (too many pods, and too much leaf and stem area). Reasonable yields (3-4.1 t ha^{-1}) of rape were possible with low N supplies < 50 kg ha^{-1} N (i.e. from relatively small amounts available from mineralisation in the soil). The optimum soil N supply was about 125 kg ha^{-1} N, although the curve was plateau-like over the range 100-150 kg ha^{-1} N. However, even at this N supply, yield showed very great variation from 3.6 – 5.6 t ha^{-1}. This variation was due to other factors other than nitrogen supply and resultant crop size affecting yield. For example, despite an adequate nitrogen supply uptake could be limited by poor rooting, drought conditions *etc.* and even after development of an adequate canopy yield could be limited by poor incident light conditions, as discussed elsewhere. Yield was increased by a maximum of about 1.6 t ha^{-1} by the optimum nitrogen supply, and could be decreased by about 1 t ha^{-1} by an oversupply of N.

3.3. Timing and splitting of nitrogen application.

The data in the section above indicate that large early applications of nitrogen may increase N supply and therefore cause a LAI above the optimum before flowering, which Appendix I showed does not contribute to yield. On the other hand, an additional supply of up to 70 kg ha^{-1} N was needed over that required to produce critical pre-flowering LAI to produce optimum pod numbers, so a late application could provide N for pod development without the production of an excessive LAI. The timing and splitting of nitrogen applications was studied in 1996. Applications were split equally and applied on the 1st and 25th March (Table 4), or were all applied early or all applied late. The results are shown in Table 1 and Figure 1. With the split application, the highest yield was from the zero fertilised plots (4.8 t ha^{-1}) and additional nitrogen applications decreased yield (0.44 t ha^{-1} by 200 kg ha^{-1} N), due to the formation of excessively large canopies. When the early and late applications were analysed, there was no significant response to nitrogen ($P>0.1$). There was no significant difference ($P>0.1$) caused by applying all the nitrogen early or all late (Table 11), although on average, there was a numerical increase of 0.154 t ha^{-1} on average from late application of N.

Different timings and splits were not studied in 1997, although an assessment was made of the usefulness of 40 kg ha^{-1} seed bed nitrogen applied in the previous autumn. There was no significant difference ($P>0.1$) in yield due to seedbed N (Table 1), although on average yield was 0.20 t ha^{-1} higher when seed bed N was not applied. This was a year when the SMN levels in February were relatively low (49 kg N ha^{-1}), although SMN in the previous autumn was not measured. In 1998, the effect of early applications of nitrogen was studied, but again there were no significant ($P>0.1$) effects. When no late nitrogen was applied, there was a numerical increase in yield of 0.16 and 0.36 t ha^{-1} respectively over zero fertilised plots when 50 or 100 kg ha^{-1} N was applied early. With late applications of 80 kg ha^{-1} N, early applications of 50 or 100 kg decreased yield by 0.33 and 0.21 t ha^{-1} respectively compared to no early application. With 160 kg N ha^{-1} applied late, the 50 kg ha^{-1} N early application increased yield by 0.15 t ha^{-1} and the 100 kg N ha^{-1} early application decreased yield by 0.12 t ha^{-1}. However, differences were not statistically significant ($P>0.1$). In 1999, no assessment of different timings or splits of nitrogen were made. However, various canopy management strategies were tested. Although yields were not significantly different, application of one dose of 80 kg ha^{-1} N gave the highest yields, with larger N applications reducing yield slightly. Assessment of the effects of applying 80 kg ha^{-1} N as foliar urea (40 kg ha^{-1} at end of flowering, followed by 40 kg ha^{-1} two weeks later) showed no difference in yield to zero N application.

3.5. Economic optima for nitrogen fertilisation

The profit margin of crop value over N use (yield* seed price)- (N application rate*N cost) can be plotted against N application rate. Assuming the current price of £110 t^{-1} for rapeseed and £0.30 kg^{-1} for N (Nix, 1998), a series of lines or curves can be plotted for the different years. The figures show the curves and equations for a price of N = £0.30 kg^{-1}, the approximate price throughout the period of the research (Nix, 1996-1999). However, since that time the price of nitrogen fertiliser has risen substantially to about £0.40 kg^{-1} (Nix, 2000) so equations for this value of N are also given.

Figure 10 shows that in 1996, margin decreased linearly with increased nitrogen application as yield was reduced. The significant ($P<0.001$) equation Margin (£ ha^{-1}) = 508 – 0.354*N (and Margin = 508 – 0.454*N at N= £0.40 kg^{-1}) accounted for 73% of the variation and in this year there was no economic benefit from N fertilisation since soil mineral N was sufficient to provide the critical crop size and further fertilisation produced crops that were too large. Since the price of N has increased, the economic penalty of over fertilisation has become greater, as margins in the second equation drop with a steeper gradient with excess N.

Figure 11: margin of crop value over cost of N fertilisation, Sutton Bonington 1996.

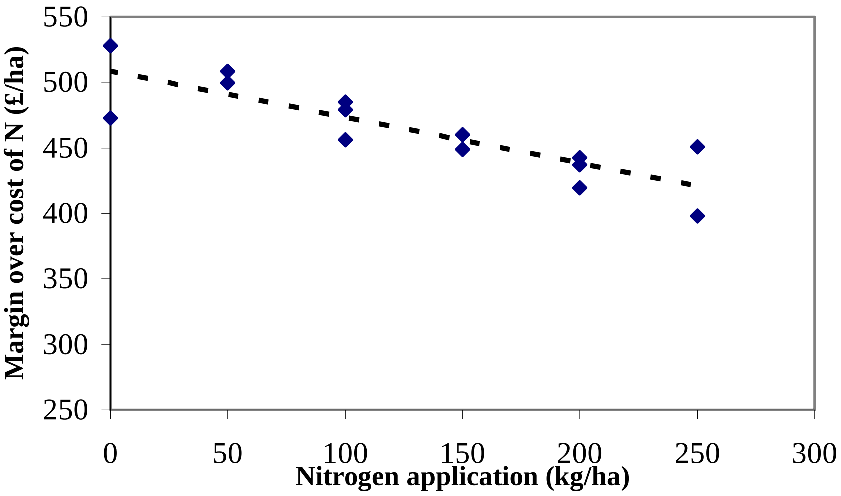


Figure 12: Margin of crop value over cost of N fertilisation, Sutton Bonington 1997.

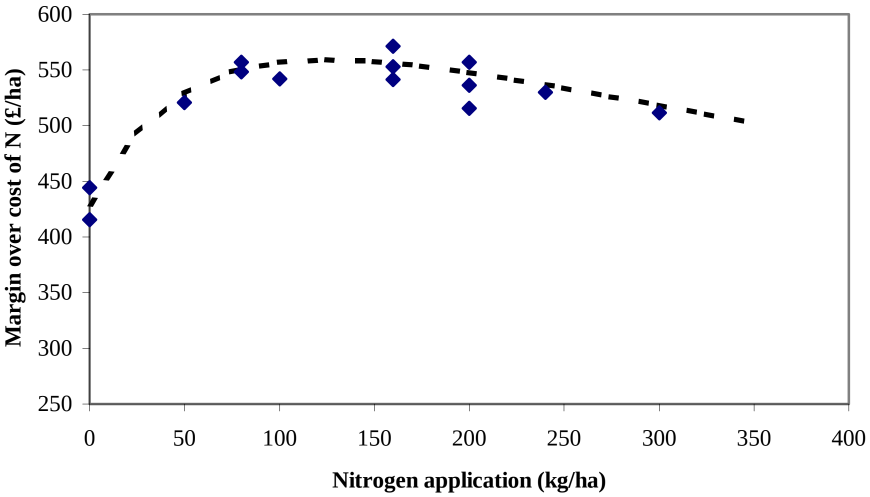


Figure 13: margin of crop value over cost of N fertilisation, Sutton Bonington 1998.

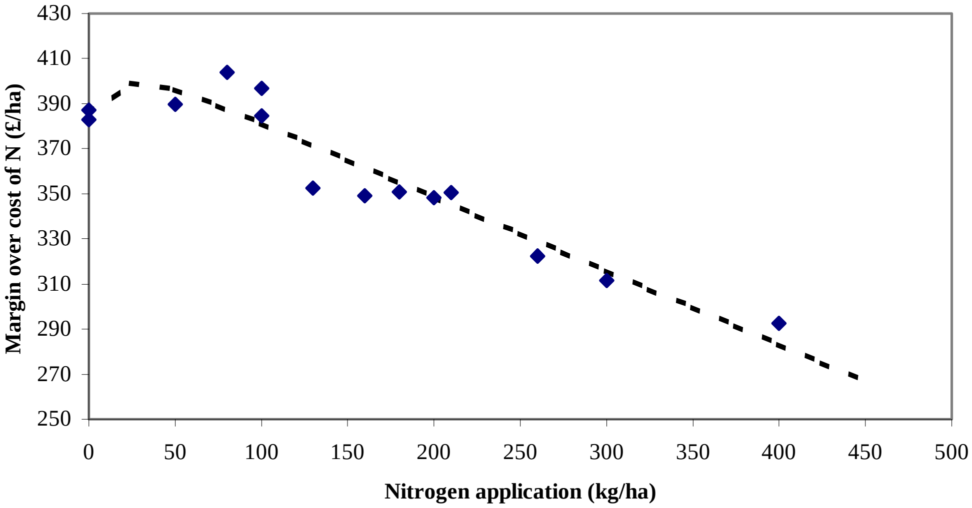
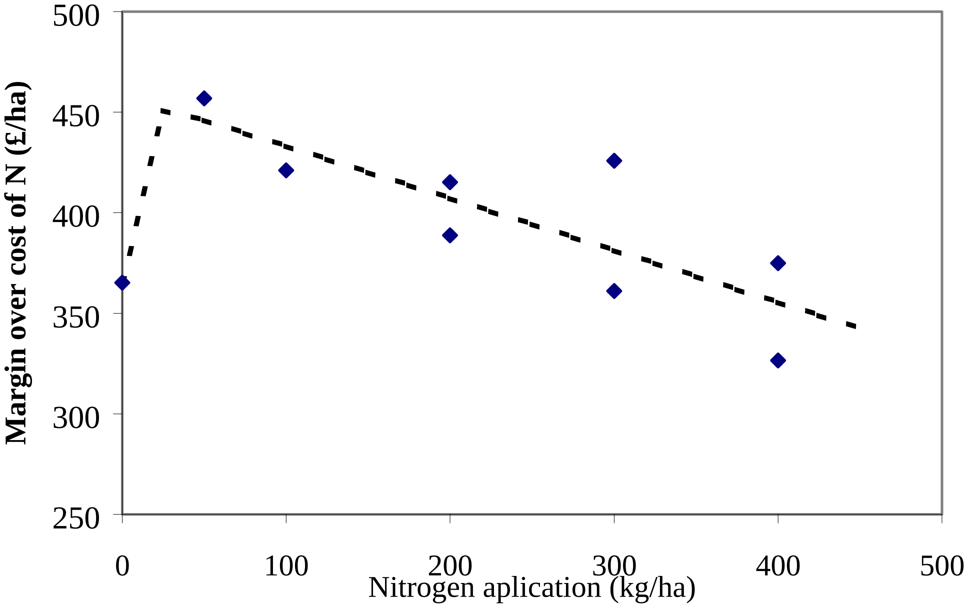


Figure 14: Margin of crop value over cost of N fertilisation, Sutton Bonington 1999.



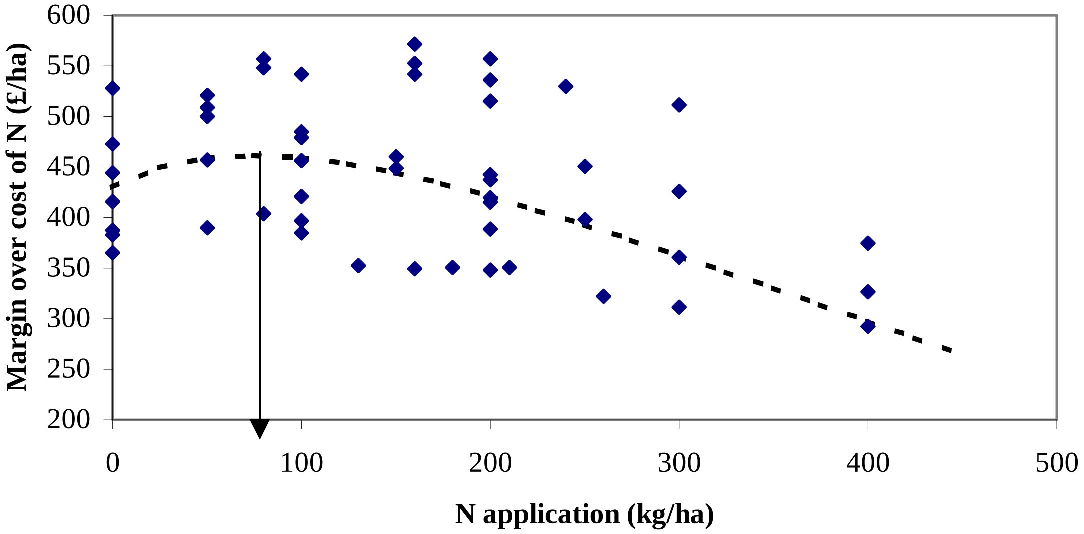
In 1997, there was a significant ($P<0.001$) linear plus exponential relationship between margin and N application (Figure 12), accounting for 89% of the variance with the equation Margin = 617 – 187*$(0.981)^N$ – 0.356*N (Margin = 617 – 187*$(0.981)^N$ –0.456*N at N = £0.40 kg^{-1}). Thus, optimum margin was achieved from an application of about 100 kg ha^{-1} N in both cases, with decrease in margin due to over-application of N (with a greater penalty with increased N cost). This was because soil mineral N reserves in February were low and the additional N allowed canopy to grow and reach the optimum size for yield formation, compared to zero fertilised plots. However, there was a penalty of over-application of nitrogen with reduced yield as the canopy became too large. A similar response was found for both the low and high plant population experiments, although the high population data was explained by a separate equation indicating a more deleterious effect of over-fertilisation by N.

The response in 1998 (Figure 13) was again linear plus exponential. The significant ($P<0.001$) equation, Margin = 414 – 28.8*$(0.943)^N$ – 0.327*N, accounted for 89% of the variance. At £0.40 kg^{-1} N the equation was Margin = 414 – 28.8* $(0.943)^N$ – 0.427*N, again causing a steeper penalty of over-application of N. Thus, optimum nitrogen fertilisation was only 50 kg ha^{-1}, with a steep decrease in margin with over application as in the previous years. Thus was unexpected since February SMN levels were low, which would be expected to limit canopy growth and yield. However, this is consistent with 1998 being a dull year when the optimum canopy size for the light available would be relatively small, for which SMN was sufficient.

In 1999 the linear plus exponential equation relating N application and margin at N= £0.30 kg^{-1} was just non-significant at the 10% level ($P = 0.111$). The equation, Margin = 459 – 94.2*$(0.852)^N$ – 0.2589*N accounted for 47% of the variance (Figure 14). However the relationship at N = £0.40 kg^{-1} (Margin = 459 – 94.2*$(0.852)^N$ – 0.3589*N) was significant ($P = 0.43$), accounting for 65% of the variance. In both cases, the optimum level of N fertilisation was about 60 kg ha^{-1}. was observed in 1999, as in 1997, with the equation: margin = 0.295*N – 0.001*N^2 + 442. This accounted for 44% of the variance and gave optimum margin at a nitrogen application rate of 148 kg ha^{-1} N, lower than in 1997 (Figure 14). However, SMN in February was 27 kg ha^{-1} higher in 1999 than in 1997.

Pooling all of the data gave a significant ($P = 0.013$) but weak (accounting for 15% of the variance) overall regression between N application and margin, following a linear plus exponential form, given by the equation Margin = 568 – 138*$(0.988)^N$ – 0.674*N (or Margin = 568 – 138*$(0.988)^N$ – 0.674*N at £0.40 $kg^{-1,}$ $P = 0.001$ accounting for 24% of the variance) (Figure 15). Solving this equation for optimum margin gives an optimum N fertilisation rate of 90 - 100 kg N ha^{-1} over the years and conditions of this work of this work. This is considerably less than the book recommendation for oilseed rape at the time of the research (Anonymous, 1994) which could be up to 230 kg ha^{-1} N, on an Index 0 soil (i.e. after barley).

Figure 15: Margin of crop value over cost of N application, all data 1996-1999.



Obviously this 'book' recommendation, not taking actual SMN values and the demand of the crop into account, would have resulted in over application of N to most of the crops in this study. An assessment of the margins produced from following the book recommendation compared to targeting N application based on supply (i.e. taking into account SMN in February) and demand is given in Table 2. This assessment uses the equations of the curves for each individual year to calculate the margin for each strategy, based on N applications of 230 kg ha^{-1} N from the book recommendation, and based on (125 – SMN_{Feb})/0.6 for the targeted application, with the optimum value of 125 kg ha^{-1} determined from the overall relationship of N supply to yield (Figure 10). A zero N strategy is also included. If this value was negative, an assumption that zero N should be applied was made. The margins are given for the current price of nitrogen at £0.40 kg^{-1} (Table 2).

Table 2: Margins of crop value over N price for various N application strategies (Sutton Bonington 1996 – 1999.

Year	SMN$_{Feb}$	Targeted N application (kg ha^{-1})	Margin (£ ha^{-1})		
			Zero	Targeted Application	Book
1996	165	0	508.00	508.00	403.58
1997	49	127	430.00	542.73	509.85
1998	44	135	385.20	356.34	308.32
1999	76	82	365.00	429.57	376.45
Average margin (£ ha^{-1})			422.05	459.16	399.62
Average loss in margin (£ ha^{-1})			37.11	0.00	59.54

Table 2 shows that the strategy of targeting N application based on the soil mineral N in February was most profitable (although the costs of SMN determination and N application were not accounted for). Both zero fertilisation and book recommendations (over application) reduced margins, by £37 and £59 ha^{-1} respectively. In 1996 and 1998, zero application was equivalent to, or more profitable than, the targeted application. In 1996 this was due to the very high SMN reserves in February, which were sufficient to provide for optimal crop growth. In 1998, this was probably due to the very dull light conditions during pod filling, which made large canopies unsuitable. Following the book recommendation was always less profitable than targeted N, although in 1997 and 1999 when SMN in February was quite low, the book recommendation was more profitable. In 1999, however, the book recommendation only produced £11 ha^{-1} more than zero fertilisation. At the lowest level of SMN in 1997, the ‘book’ strategy gave a £79.85 ha^{-1} benefit over zero application. However, averaged over the experiments, under the soil fertility conditions at Sutton Bonington, under fertilisation (zero N) caused a smaller reduction in margin than over supply of N. When fixed and variable costs of N application are taken into account, the zero N strategy may compare favourably with even the targeted N strategy and the margin over excess N application would increase still further.

4. Conclusion

The results indicated that the economic optimum for nitrogen fertilisation at Sutton Bonington was quite low compared too much current commercial practice, with a soil nitrogen supply (SNS) of 125 kg ha^{-1} necessary for optimum yield. Excess nitrogen fertilisation could cause a greater yield penalty than under-fertilisation, due to over-production of leaf and pods. Although economic optima for N fertilisation will vary widely depending on soil conditions, the results demonstrate the usefulness of knowledge of SMN for adjusting N inputs, as the most profitable strategy came from ensuring the supply of about 125 kg ha^{-1} N which in some years could be gained from the soil with no applied N.

APPENDIX IV: Effects of spray management strategies on pest and disease incidence, yield and net margins of oilseed rape

1. Introduction

The previous sections have shown that large oilseed rape canopies (in both vegetative and reproductive stages) offer little or no benefit to producers in terms of increased yield. Various agronomic strategies whereby more moderately-sized canopies could be grown have also been demonstrated. One of the potential benefits of growing more moderate canopies identified at the beginning of the research was the possibility that smaller canopies would experience less pressure from pests and disease than more lush canopies and would therefore require fewer pesticide and fungicide inputs. The major fungal diseases of relevance to oilseed rape in the UK include light leaf spot, phoma canker, sclerotinia stem rot and alternaria leaf and pod spots (Rimmer and Buchwaldt, 1995, Hardwick *et al.*, 1991). For example light leaf spot (*Cylindrosporium concentricum*), sclerotinia (*Sclerotinia sclerotiorum*) and alternaria (*Alternaria brassicae*) are believed to be exacerbated by a moist microclimate, which could be expected in a denser canopy due to limitation of free air flow. *Sclerotinia* and grey moulds (*Botrytis spp.*) are particularly prevalent after flowering and during leaf fall when petals, bearing the inoculum, become stuck to stems and branches of oilseed rape plants. Denser crops usually have a far greater number of petals, theoretically increasing the risk of petal adhesion. Consequently, smaller canopies might have a lower requirement for fungicide input. In England, approximately 60% of crops receive applications of insecticides. In more sparse crops, where pods borne on branches contribute to a considerable portion of the yield, flowering occurs over an extended period compared to denser crops where there is little or no branching. This may offer the pollen beetle (*Meligethes aeneus*) the opportunity to cause more damage. Similarly, other insect pests *e.g.* seed weevil (*Ceutorhynchus assimilis*), could conceivably be more damaging in crops with fewer pods. It is therefore possible that sparse canopies may have lower thresholds for insecticide treatment. However, many crops are sprayed with insecticides when populations are below critical threshold values an d so there may also be scope for reduction of pesticide inputs.

2. Materials and Methods

The hypothesis that different canopy sizes may require distinct fungicide and insecticide inputs was tested at ADAS Rosemaund in 1998 and 1999. An attempt to produce canopies of different size was made by varying sowing date (early September/early October) and seed rate (120 seeds m^{-2}/60 seeds m^{-2} as in previous years (see Appendices I and II). These crops were then managed in different ways as shown in Table 1 below. The actual fungicide and insecticide spray applications and dates used in each regime are shown in Table 2 (1998) and 3 (1999).

Table 1: Insecticide and fungicide management strategies, 1998-1999

Treatment	Insecticide	Fungicide
1.	Prophylactic	Untreated
2.	Prophylactic	Managed
3.	Prophylactic	Prophylactic
4.	Managed	Prophylactic
5.	Untreated	Prophylactic

Table 2: Fungicide and pesticide applications, 1998

Sowing Date	**Treatment**	**Date of application, rate (l ha^{-1}) and product code**						
		Nov	Dec	Jan	Feb	March	April	May
Early	1	0.7Gc	*	*	*	*	0.2A	0.2A
	2	0.4 P 0.7Gc	*	0.4P	*	*	0.2A	0.2A
	3	0.4P 0.7Gc	*	0.4P	0.4P	*	3C, 0.5De 0.2A	* 0.2A
	4	0.4P	*	0.4P	0.4P	*	3C, 0.5De	*
	5	0.4P	*	0.4P	0.4P	*	3C, 0.5De	*
Late	1	0.7Gc	*	*	*	*	0.2A	0.2A
	2	0.4P 0.7Gc	*	0.4P	*	*	0.2A	0.2A
	3	0.4P* 0.7Gc	0.4P	*	0.4P	*	3C.0.5De 0.2A	0.2A
	4	0.4P	*	0.4P	*	0.4P	*	3C, 0.5De
	5	0.4P	*	0.4P	*	0.4P	*	3C, 0.5De

Gc = Gamma-col (insecticide), A = Acquit (insecticide), P = Punch C (fungicide), C = Compass (fungicide), De = Derosal (fungicide)

Table 3: Fungicide and pesticide applications, 1999

Sowing date	Treatment	Date of application, rate ($l\ ha^{-1}$) and product code				
		9/10	22/3	8/4	29/4	25/5
Early	1	0.2A	*	0.5D	*	*
	2	0.2A	*	0.5D	3C	*
	3	0.2A	0.5P	0.5D	3C	*
	4	*	0.5P	*	3C	*
	5	*	0.5P	*	3C	*
Late	1	*	*	0.5D	0.5D	*
	2	*	*	0.5D	0.5D	*
	3	*	0.5P	0.5D	0.5D	3C
	4	*	0.5P	*	0.5D	3C
	5	*	0.5P	*	*	3C

A = Acquit (insecticide), P = Punch C (fungicide), D = Decis (insecticide), C = Compass (fungicide).

Growth analyses were performed and yield determined as described previously (Appendixes I and II).

In 1998, the crops were monitored for pollen beetle (*Meligethes aeneus.*) numbers in April and for pollen beetle, cabbage stem flea beetle (*Psilliodes chrysocephala*) and seed weevil (*Ceutorhynchus assimilis*) activity in May by counting the number of insects on each of 20 plants using standard identification keys protocols. In 1999, pollen beetle numbers only were recorded in April. These species are recognised as the major insect pests of oilseed rape in Europe (Ekbom, 1995). Samples of 10 plants from each plot were scored, and an average disease severity derived, for the following foliar diseases in November, March and April: light leaf spot (*Cylindrosporium concentricum/Pyrenopeziza brassicae*), alternaria/dark leaf and pod spot (*Alternaria brassicae*), phoma (*Phoma lingam/Leptosphaeria maculans*) and downy mildew (*Peronospora parasitica*) using standard disease assessment protocols. In July, leaves were scored for *Alternaria* and *Botrytis*, stems for *Sclerotinia sclerotiorum, Alternaria* and light leaf spot and pods for *Alternaria* and light leaf spot. Canker (*Phoma lingam*) on stems was assessed in August in 1998 but not 1999 when disease levels were very low.

3. Results and Discussion

3.1. Crop size

The variation in crop size due to seed rate and sowing date effects in 1997/1998 and 1998/1999 is shown in Tables 4 (1998) and 5 (1999). Crop size was assessed during early flowering on 3rd May 1998, during flowering on 10th June 1998 and 28th June 1999 and also pre-harvest (7th July 1998, 17th-29th July 1999: data not shown).

Table 4: 1998 pre-flowering and mid-flowering growth analysis of the different crops used for spray management strategy studies

Sowing Date	**Seed Rate**	**3rd May**		**10th June**		
		Plants m^{-2}	Total GAI	Total GAI	Pod GAI	Pods m^{-2}
Early	120	73	4.53	3.93	0.71	6402
Early	60	44	4.41	3.64	0.94	6209
Late	120	78	3.30	3.81	1.17	6912
Late	60	55	3.10	3.31	1.23	6107
SED[a]		21	1.05	1.09	0.38	1257
SED[b]		28	0.20	0.90	0.26	818

[a] Sowing date x seed rate

[b] In the same level of sowing date

Table 5: 1999 mid-flowering growth analysis of the different crops used for spray management strategy studies

Sowing Date	Seed Rate	28th June			
		Plants m^{-2}	Total GAI	Pod GAI	Pods m^{-2}
Early	120	52	3.28	1.90	11429
Early	60	32	3.21	1.92	10515
Late	120	68	3.24	2.01	8587
Late	60	42	3.19	1.81	10054
SED[a]		9.0	1.67	0.82	2212
SED[b]		7.5	0.13	0.20	2072

[a] Sowing date x seed rate

[b] In the same level of sowing date

In 1998, there were no significant effects (P>0.1) in any growth analysis parameter, due to the large degree of inter-plot variation and the relatively few degrees of freedom, which caused large least significant differences at the 5% level. In 1999, the only significant effect was that of seed rate on plant population (P = 0.002), with significantly more plants in the high seed rate crops compared to the low seed rate crops. Neither sowing date nor seed rate significantly (P>0.1) affected crop size during flowering in either year, although in both years the seed rate effect was close to significance at the 10% level (P = 0.1 – 0.2) for some growth analysis parameters. Time of sowing effects were usually above a P-value of 0.25 and there was never any indication of a time of sowing x seed rate interaction (P>0.5). In 1998 the early-sown crops had numerically larger GAIs due to more leaf earlier in development (Table 4), although at the later growth analysis this difference had disappeared and the GAI of pods appeared to be numerically greater in the late-sown crops despite there being very similar pod numbers. There were also numerical indications of higher plant numbers in the high seed rate crops in 1998. In 1999, there were no indications of any numerical differences between any of the crops, even though there were significantly more plants m^{-2} in the high seed rate crops.

It was therefore not possible to fully assess the different requirements of large and small canopies for fungicide and pesticide inputs as the pod canopies were so similar in size, with only an indication that the early sown crops in 1998 could be larger than the other crops. However, the effects of different fungicide and insecticide inputs on these similarly sized canopies were assessed. Although the crops were of similar size in terms of green area index, the individual plants making up the canopies of the different seed rate treatments were substantially different. The plants in the high seed rate crops bore more green area and pods per plant and had thicker stems than the low seed rate crops, due to the compensatory growth discussed in Appendix I.

3.2. Disease and pest levels

The fungicide and pesticide applications composing the different treatments for 1998 and 1999 are shown in Tables 2-3. In 1998 the ‘managed’ pesticide regime was no insecticide. In 1999 on the late-sown crops the ‘managed’ fungicide regime was no application. On the early-sown crops in 1999 the ‘managed’ pesticide regime of the early-sown crops was no insecticide. In the 1997/1998 season, foliar diseases were first assessed on 6th November 1997. No *Phoma* or *Alternaria* infection was detected. Low levels of downy mildew and light leaf spot were recorded (data not shown) in the low and high seed rates of the second sowing date plots respectively. At this date the different management regimes had not yet been applied so there were no ‘management’ differences. On 26th March 1998, the crops were again assessed for foliar diseases. The four fungi assessed (light leaf spot, alternaria, phoma and downy mildew) were present at barely detectable levels (data not shown) that were not significantly different between time of sowing, seed rate or management treatments.

At the next disease assessment date on 16th June, diseases on the leaves, stems and pods were assessed separately. On the leaves, some botrytis infection was recorded but virtually no alternaria was observed (Table 6). There was a numerical indication of slightly more botrytis in the earlier sowing date, but this effect was just non-significant ($P = 0.070$) and there was no significant effect ($P = 0.339$) of management treatment on the level of botrytis infection.

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Table 6: Disease scores for untreated, managed and prophylactic fungicide treatments of different canopies, 16th June 1998

Disease	Disease Score											
		Late	Early									
		120			60			120			60	
	U	M	P	U	M	P	U	M	P	U	M	P
Leaf botrytis	6.38	6.29	6.10	6.50	6.69	6.39	5.74	5.67	5.13	6.18	5.67	7.35
Leaf alternaria	0.00	0.00	<0.01	<0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stem sclerotinia	1.50	0.38	0.11	0.58	0.63	0.16	0.60	0.18	0.00	0.28	0.10	0.00
Stem alternaria	1.34	1.88	0.26	3.34	1.23	0.10	0.18	0.68	0.04	0.33	0.05	0.04
Stem light leaf spot	9.63	3.00	1.84	5.05	3.89	2.12	3.63	4.22	2.53	4.28	4.06	1.82
Pod alternaria	0.35	0.56	0.44	0.09	0.01	0.48	0.94	0.40	0.27	0.92	0.25	0.20
Pod light leaf spot	5.28	3.85	4.17	2.45	3.22	4.34	4.87	2.88	5.88	6.71	5.20	4.10

U = untreated, M = managed, P = prophylactic

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Table 7: Disease scores for untreated, managed and prophylactic fungicide treatments of different canopies, 17th July 1998

Disease	Disease Score											
	Late						Early					
	120			60			120			60		
	U	M	P	U	M	P	U	M	P	U	M	P
Leaf botrytis	2.63	8.85	4.78	3.63	6.58	4.23	2.23	2.98	3.13	6.95	4.53	3.41
Leaf alternaria	0.00	0.00	0.00	0.00	<0.01	0.00	0.00	0.00	0.00	0.05	0.00	<0.01
Stem sclerotinia	0.03	0.00	0.38	0.15	0.05	0.00	0.05	0.00	0.00	0.20	0.00	0.00
Stem alternaria	<0.01	<0.01	<0.01	0.00	0.00	<0.01	0.00	0.00	0.00	0.00	0.03	<0.01
Stem light leaf spot	7.14	3.1	0.33	8.99	1.18	0.38	1.58	0.66	0.29	2.09	0.91	0.46
Pod alternaria	<0.01	0.00	0.42	0.13	<0.01	<0.01	<0.01	0.00	<0.01	0.00	0.00	0.00
Pod light leaf spot	2.63	1.47	0.38	5.20	0.20	0.21	2.61	0.02	0.53	1.26	0.10	0.05
Phoma canker*	2.43	1.50	0.30	3.28	1.80	0.83	2.23	1.20	0.48	1.65	0.78	0.40

U = untreated, M = managed, P = prophylactic   * Assessed 7/8/98

Of the stem diseases, there was very little alternaria or sclerotinia on 16th June (Table 6) and no significant effects of agronomic or fungicide treatment on these diseases at this date. However, there were numerical indications of more sclerotinia infection in the early sowings, high seed rates and no fungicide treatments. For alternaria, there was a numerical indication of more infection in the no fungicide treatments (1) of the early sowings. There was more light leaf spot infection on the stems than either alternaria or sclerotinia. There was significantly more light leaf spot ($P = 0.002$) in the earlier sowing and in the no fungicide treated plots of the early (but not the late) sowing (Table 6). The pod disease alternaria was again present in low levels, but with no significant agronomic or spraying effects. There was more light leaf spot activity on the pods (Table 21) with significantly ($P = 0.008$) more light leaf spot infection in the non-fungicide treated plots (Table 6).

At the next disease assessment on 17th July 1998 (Table 7), leaf diseases were at very low levels and leaves were a very small part of the canopy at this time: there was no detectable alternaria infection and although there was some botrytis (less than in the previous assessment), there were no significant ($P>0.1$) treatment effects. Scores for stem diseases alternaria and sclerotinia were insignificant (Table 7). As at the previous assessment date, the greatest level of stem infection was from light leaf spot: there was significantly more ($P<0.001$) fungal infection of this type on stems of non-fungicide treated plots than on managed plots which in turn had more activity than the prophylactic treatment. Levels were significantly greater ($P<0.001$) in the early sowings compared to the late sowings. At the final assessment, scores for pod alternaria was insignificant. Whilst the score for pod light leaf spot was also relatively low, there was an indication of more activity in the non-fungicide plots (1) compared to the managed plots and prophylactic treatments. The phoma canker assessment taken on 7th August 1998 showed a relatively low severity index. Although canker infection was more severe in no-fungicide sprayed plots ($P<0.05$), there was no difference in infection between the different crop types (Table 7).

Assessment of pollen beetle activity on 27th April 1998 showed insignificant amounts of these insects, with less than one adult per plant in all treatments and no significant treatment effects (data not shown). On 15th May 1998, greater levels (about 3 per plant) of pollen beetle activity were recorded, although no significant differences were found between treatments. Seed weevil and flea beetle activity also showed no significant differences between plots on 15th May and numbers were low. There were less than 0.3 seed weevil adults per plant and flea beetles were almost undetectable. This level of insect activity is below the threshold for spray action.

In 1999, fungal diseases were assessed on 24th June and 7th July. All diseases were present at very low levels and no significant differences between agronomic or spray treatments could be detected at the 5% level (data not shown). The pollen beetle numbers assessed on 27th April were also uniformly low (zero adults found in most plots, data not shown) with no detectable treatment effects. Due to the low levels of insect pests and fungal diseases, further assessment of seed weevil, flea beetle and stem canker were not made.

3.3. Effects of management strategy on yield

The yield (corrected to 91% dry matter) from the different agronomic and fungicide-insecticide treatments is shown in Table 8.

Table 8: Yields from different canopies managed with different fungicide and pesticide regime (double prophylactic regime shown in bold)

Year	Sowing Date	Seed Rate	Yield ($t\ ha^{-1}$) and management						
			Treatment	1	2	3	4	5	Crop Mean
			Fungicide[a]	U	M	P	P	P	
			Insecticide[a]	P	P	P	M	U	
1998	Early	120		3.99	4.78	**5.19**	4.87	4.84	4.73
1998	Early	60		4.10	4.68	**4.82**	4.64	5.13	4.67
1998	Late	120		3.31	3.74	**4.08**	3.74	3.79	3.73
1998	Late	60		3.55	3.65	**4.31**	4.12	4.45	4.02
Treatment mean				3.74	4.22	**4.60**	4.34	4.55	4.29[b]
1999	Early	120		2.98	3.38	**3.17**	3.35	3.53	3.28
1999	Early	60		2.59	2.74	**2.75**	3.23	3.16	2.89
1999	Early	120		3.28	3.10	**3.14**	2.87	2.67	3.01
1999	Early	60		2.74	2.71	**2.80**	2.92	2.66	2.77
Treatment mean				2.90	2.98	**2.97**	3.09	3.01	2.99[b]

SED (1998) Sowing x seed rate x treatment = 0.430 (0.345 in same seed rate x sowing level)

SED (1999) Sowing x seed rate x treatment = 0.414 (0.338 in same seed rate x sowing level)

[a] P = prophylactic, M = managed, U = untreated [b] Yearly grand mean.

In 1998, the sowing date effect was on the borderline of significance (P = 0.059), with greater yields (0.82 t ha^{-1} on average) from the earlier compared to the later sowing. This was presumably an effect of the timing of seed filling interacting with weather conditions since pod numbers and canopy sizes were otherwise similar (Table 20). Seed rate had no significant effects (P = 0.37) with equivalent yields derived from 120 and 60 seeds m^{-2} rates. Management treatment had a very significant ($P<0.001$) effect on yield in 1998. This was due to the significant yield penalty caused by not controlling fungal disease (treatment 1, 0.86 t ha^{-1} less on average than treatment 3 where fungicides and insecticides were applied prophylactically, Table 9). Presumably this was due to infection of stems and pods by significantly greater amounts of light leaf spot (*Cylindrosporium concentricum*), which was present at significantly higher levels in the non-fungicide treated plots. When insecticides were applied prophylactically, the loss of yield from no control of fungal disease (1.20 t ha^{-1}) was numerically greatest in the early 120 seeds m^{-2} crop (theoretically the largest canopy). There were slight numerical indications of more stem and pod light leaf spot infection in the early sown treatments, although demonstration of statistically significant differences was not possible due to the generally low and similar levels. However, a slightly higher rate of infection could explain the greater yield loss in this crop due to not controlling fungal pathogens, compared to the late sown crops. Also, due to the higher number of stems in the high plant population, more stems per m^{2} would be affected by a similar recorded disease severity to the low seed rate crop (which was assessed on a fixed number of plants rather than plants from a fixed area). The greater level of light leaf spot infection could be due to the greater leaf area early in development allowing build up of fungal inoculum. In the other three canopy types there was a similar loss in yield (0.72 – 0.76 t ha^{-1}) from not using fungicide. The 'managed' approach to fungicide application in 1998 caused less yield loss compared to prophylactic treatment than not using fungicide (Table 9), in the region of 0.14-0.66 t ha^{-1}, but only the 0.66 t ha^{-1} lower yield in the late-sown low seed rate crop was significantly different from the prophylactic control at the 5% level of significance.

In 1998 when fungal disease was controlled by prophylactic fungicide, using the 'managed' approach to pesticide application (*i.e.* using no insecticides) caused no significant yield penalties ($P>0.05$). The greatest yield difference was 0.21 t ha^{-1} greater than the prophylactic control.

Table 9: Difference in yield from control (prophylactic spraying) of managed and untreated fungicide and insecticide regimes (in the presence of prophylactic insecticide and prophylactic fungicide respectively)

Sowing Date	**Seed Rate**	**Yield difference from control (t/ha)**			
		1998		1999	
		Untreated	Managed	Untreated	Managed
Fungicide					
Early	120	**-1.20**	-0.41	-0.19	+0.21
Early	60	**-0.72**	-0.14	-0.16	-0.01
Late	120	**-0.77**	-0.34	+0.14	-0.04
Late	60	**-0.76**	-0.66	-0.06	-0.09
Treatment mean		**-0.86**	-0.39	-0.08	+0.02
Insecticide					
Early	120	-0.35	-0.34	+0.18	+0.36
Early	60	-0.18	+0.31	+0.48	+0.41
Early	120	-0.34	-0.29	-0.27	-0.13
Early	60	-0.19	-0.14	+0.12	-0.03
Treatment mean		-0.27	-0.12	+0.13	+0.15

Yield changes significant at the 5% level (within the same sowing date x seed rate level are shown in bold)

In 1999, the only significant effect (P = 0.002) was of seed rate, with slightly reduced yields derived from 60 seeds m^{-2} compared to 120 seeds m^{-2} seed rates. However, the reduction was small (0.32 t ha^{-1} on average). Neither sowing date nor management treatment were significant (P>0.5). The 5% LSD was 0.675 t ha^{-1}. Thus, when insecticides were applied prophylactically, the maximum yield penalty from not using fungicide was about 0.35 t ha^{-1}. The penalty from the ‘managed’ fungicide approach (*i.e.* no fungicide applied to early-sown crops) was similar and non-significant. When fungicides were applied prophylactically, the maximum difference from prophylactic insecticide management was 0.48 t ha^{-1} greater yield where insecticide was not used (Table 24).

3.4. Margin of yield value over cost of spray applications

1998 and 1999 were not good seasons for assessing the effects of insecticide and fungicide inputs on pest and disease pressure in differently sized canopies of oilseed rape. Firstly, the canopies produced did not differ significantly in size during the most critical pod filling phase, due to the compensatory growth capacity of oilseed rape (Appendix 1). However, there was a numerical indication of slightly greater leaf area early in development in the early sown and high seed rate crops which could affect fungal infection and development. Secondly, the pressure from pests and diseases were relatively low with the only significant differences being increased stem and pod light leaf spot infection in non-fungicide treated plots (with an indication of slightly greater disease pressure in the early sowing). There was no indication of any significant difference in insect pressure in any year (although levels of activity were uniformly low). In 1998, the lack of fungicide treatment significantly decreased yield and in 1999, there were no significant differences in yield apart from a small seed rate effect. The loss of yield in 1998 can only be attributed to increased stem and pod light leaf spot infection. As the data is so inconclusive, it is not possible to fully assess the potential differences in management strategies for large and small canopies.

However, an economic assessment of the benefits (if any) of the spray applications can be made. Table 10 shows the costs of the spray chemicals used. Each application was calculated to cost £6.35 ha^{-1} (Nix, 1998). This information, together with that in Tables 2, 3 and 8 was used to calculate the margin of crop value over chemical costs. The value of the crop was assumed to be 110 t ha^{-1} (Anonymous, 1999).

Table 10: Costs of chemical sprays per litre

	Chemical					
	Acquit	Derosal	Decis	Compass	Punch C	Gammacol
Cost (£ l^{-1})	16.00	5.85	16.50	10.00	31.36	9.40

The net margins of yield over the costs of spray application are shown in Table 11.

Table 11: Margins of crop value over fungicide and insecticide (including application) cost for different crops and spray application regimes, 1998-1999

Year	**Sowing Date**	**Seed Rate**	**Yield (t/ha) and management**

		Treatment	1	2	3	4	5	Crop
		Fungicide[a]	U	M	P	P	P	Mean
		Insecticide[a]	P	P	P	M	U	
1998	Early	120	407	**456**	443	439	436	436
1998	Early	60	419	445	402	414	**468**	430
1998	Late	120	332	**342**	327	321	327	330
1998	Late	60	358	332	352	363	**400**	361
Treatment mean			379	394	381	384	408	389[b]
1999	Early	120	304	318	267	310	**330**	306
1999	Early	60	262	248	220	**297**	289	263
1999	Early	120	**332**	312	258	238	235	275
1999	Early	60	**273**	242	221	243	234	243
Treatment mean			293	280	242	272	272	272[b]
Grand (strategy) mean			336	337	312	328	340	331[c]

[a]P = prophylactic, M = managed, U = untreated [b]Yearly grand mean [c]Mean margin over spray costs (8 x 5 year.sowing date.seed rate combinations x spray strategies).

In 1998, when insecticides were applied prophylactically, the greatest margin in the early high seed rate (E120) crop came from the managed fungicide application, at £14 ha^{-1} more than prophylactic application. Not controlling fungi in this 'large' crop caused a loss in margin of £49 ha^{-1}. In the early sown low seed rate (E60), the prophylactic approach gave the poorest margin, with the untreated and managed crops giving £43 and £17 ha^{-1} benefits respectively. In the late sown high seed rate (L120) crop the managed treatment gave the best margin at £15 ha^{-1} more than prophylactic control, although when fungicides were not used the margin was still £5 ha-1 greater than the prophylactic spraying approach. In the late-sown low seed rate (L60) crop, the best margin came from zero fungicide application, giving £6 ha^{-1} more than the prophylactic spraying and £26 ha^{-1} more than the managed treatment. Averaged over all the four crops in 1998, the best margin came from managed fungicide application, at £13 ha^{-1} more than prophylactic spraying. Use of no fungicide only yielded £2 ha^{-1} less margin than prophylactic spraying.

When fungal activity was controlled by prophylactic fungicide application, prophylactic insecticide application gave only £4 and £7 ha^{-1} more than the managed and no insecticide treatments respectively in the E120 crop. In the E60 crop, the largest margin came with no insecticide application. Managed and prophylactic insecticide treatments caused reductions of £54 and £62 ha^{-1} respectively. Equivalent margins were produced in the L120 crop from prophylactic or no insecticide use, with a £6 ha^{-1} reduction in the managed regime. In the L60 crop the greatest margin again came from no insecticide application, with the managed strategy producing £37 ha less and the prophylactic treatment £48 ha^{-1} less. Averaged over the four crops in 1998, the greatest margin came from not using pesticide with prophylactic spraying causing a reduction of £27 ha^{-1} in margin on average.

In 1999, where diseases and pests were at even lower levels than in 1998, when prophylactic insecticide was applied, prophylactic fungicide always gave the worst margin. In the E120 crop, the managed fungicide regime gave £14 ha^{-1} more than no fungicide, which was £37 ha^{-1} more than prophylactic spraying. In the E60, L120 and L60 crops no fungicide gave £42, £74 and £52 ha^{-1} more than prophylactic spraying and the managed treatment gave £28, £54 and £21 ha^{-1} more respectively. Averaged over the four 1999 crop types, no fungicide gave the best margin, £51 ha^{-1} more than prophylactic spraying and the managed treatment gave a benefit of £38 ha^{-1} over prophylactic spraying on average.

When prophylactic fungicide applications were made, managed and no insecticide applications led to increases of £43 and £63 ha^{-1} over prophylactic spraying in the E120 crop and of £77 and £69 ha^{-1} in the E60 crop. In the L120 crop, however, prophylactic spraying gave a benefit of £20 and 23 ha^{-1} over managed and no insecticide treatments respectively. In the L60 crop benefits of £22 ha^{-1} and 13 ha^{-1} were produced by managed and no insecticide regimes. Averaged over the four crops in 1999, managed or no insecticide application gave an equivalent benefit of £30 ha^{-1} more than prophylactic spraying.

The grand or strategy mean may be considered as an assessment of the profitability of different strategies over different crops in different seasons. When prophylactic insecticide was used, the managed or no fungicide treatments gave margins £24 - £25 ha^{-1} better than from prophylactic spraying. When prophylactic fungicide was applied, managed insecticide gave a £44 ha^{-1} advantage and no insecticide gave a 28 ha^{-1} benefit. Overall, the greatest margin came from prophylactic fungicide/no insecticide strategy at £340 ha^{-1} although both the prophylactic insecticide/managed fungicide and prophylactic insecticide/no fungicide were within £4 ha^{-1} of this strategy on average. The prophylactic fungicide/managed insecticide strategy gave £12 ha^{-1} less margin and the double prophylactic spraying gave £28 ha^{-1} less.

4. Conclusion

Drawing of definitive conclusions from this work is difficult due to the lack of severe disease pressure and the similarity in canopy size between the ‘different crops’. However, the results do indicate that, as with N fertilisation, a more intensive management approach to spray requirements may be beneficial over the use of blanket prophylactic sprays. Although there was some indication of a yield penalty when prophylactic fungicide sprays were not applied to the ‘larger’ early-sown seed-rate crops, with the later crops and in the very low disease pressure year of 1999, no application of fungicide gave a benefit over prophylactic application, although the ‘managed’ approach was sometimes optimal. However, averaged over the crops grown under the conditions of this study, no fungicide gave a favourable margin. This observation supports the original hypothesis that smaller ‘canopy managed’ crops may require less fungicide input. Under the conditions of this study, blanket prophylactic sprays reduced profitability and in some cases the optimum strategy may have been for no applications (although this was not studied). The explanation for this phenomenon may be twofold. Firstly, spray applications may cause crop damage and loss of yield of up to about 0.2 t ha^{-1}. Additionally, with the current low price of oilseed rape (£110 t^{-1}) and the low disease pressure in the years of the study, the increase in yield from controlling disease was insufficient to offset the cost of application. Of course, no assessment of the fixed costs of maintaining a sprayer was made and the economic benefit of disease control will vary depending on the relative prices of the chemicals and rapeseed. At any rate, the potential benefits for careful minimisation of inputs were demonstrated. The scope for reducing insecticide inputs would appear to be greater than for reducing fungicide, and there was little penalty in not using pesticide so such sprays could be left off if careful monitoring of insect populations revealed they were below threshold figures. There would seem less scope in reducing fungicide use, which lead to up to 1.2 t ha^{-1} loss in yield in 1998. However, in 1999 late crops there appeared to be scope for reducing or leaving off fungicide sprays. Although the results should be treated with caution since the effects of using ‘managed’ fungicide regimes in years of high disease pressure are not known, they do indicate that with accurate prediction and forecasting of pest and disease pressures that savings could be made in some years. As for the fungicide, in these years of low insect pressure, there were benefits from not controlling insects with insecticide. The full factorial combination of no insecticide and no pesticide was not done in this experiment, but the indications are that the margin from this strategy would have compared favourably to the others and would have been more than the double prophylactic strategy.

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