HGCA

PROJECT REPORT No. 21

AN OPERATIONAL RESEARCH STUDY OF THE ALTERNATIVES TO THE COMBINE HARVESTER

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An operational research study of the alternatives to the combine harvester

by

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Summary

This report studies the profitability of different systems of harvesting cereal grain and straw. They aim to beat the universally used combine harvester system by exploiting one or more of the disadvantages of the combine.

A combine is very expensive and can only work if the grain and straw are sufficiently dry. Grain yield is lost by respiration while waiting for the crop to be 'combine ripe', by shedding losses, by cutterbar header losses and by threshing losses. The feed value of straw in the chaff and leaf fragments is mostly lost.

Methods of exploiting these disadvantages to produce a better method of cereal harvesting are:

a) **Grain Stripper Header** which reduces the amount of straw passing through the combine and allows harvesting to be carried out in damper conditions.

b) **Harvest the grain and straw when dry with a forage harvester and separate them at the farmstead.** This reduces grain and straw losses. In addition the harvester is much cheaper but expensive separation equipment is needed at the farmstead

c) **Harvest the grain and straw and preserve with urea; Feed to cattle.** This also removes the need for a dry crop at harvest and replaces expensive separation equipment with preservation.

d) **As proposal C but use for industrial purposes.** Separation is now needed but its use can be spread over the year. A use for the straw must be found.

The feed value of straw depends on the amount of the different fractions harvested. In barley, leaf has the best metabolisable energy content followed by chaff and nodes; in wheat, leaf is best followed by nodes, and chaff is similar to stem. In calculating feed value, the effect of degradability in the rumen is taken into account. Wheat chaff is worth only £5/ha and amounts to 0.7t/ha. However with the lost fraction of leaf, the unbaled fraction of wheat straw is worth £34/ha, amounts to 1.7t/ha and increases straw yield by 33%. The unbaled fraction in barley is worth £62/ha, amounts to 0.7t/ha and would increase straw yield by 20%. The benefit of harvesting lost parts of wheat straw is due to more of the same, not a better product. The benefit in barley straw includes this effect but the leaf fraction represents a good feed on a par with hay.

Using partial budgets to compare harvesting systems ignores the complex knock-on effects of the end of harvest being earlier or later. A whole farm model is used to calculate these effects. The results can be used in comparing low and high temperature drying, assessing the cost of unreliability due to the age of combine, assessing the optimum combine speed or assessing the value of new developments such as in combine controls and the grain stripper header. The results are shown to be not affected by the soil type.

The knock-on benefit or cost of changes to the harvest system in terms which can be used in partial budgeting exercises is

	+/earlier	-/later	Possible Cause
Start of harvest, 1 week	£11/ha	£10/ha	Grain drying
2 weeks	£18/ha	£19/ha	
Workrate, 10%	£52/h	£68/h	Reliability
Workrate in cereals, 10%	£64/h	-	Grain stripper
20%	£57/h	-	

A computer simulation of the harvesting process was adapted to provide a comprehensive analysis of harvesting with both the stripper and cutter-bar headers. This calculates the total cost of harvesting including machine capital and operating costs and shedding, header and threshing losses. The crops considered were principally barley, wheat, and oats. Six hypothetical farms were considered featuring the extremes of crop area and yields in order to highlight the situations which are best for the stripper or otherwise. Three of the farms have equal areas of wheat and barley, which is a normal distribution of crops. The three other farms have all standing wheat, which is the situation in which the stripper should have least advantage over the cutterbar, though unusual in practice.

On farms with an equal area of wheat and barley, the distribution most usually found in the UK, the stripper header was better than the cutterbar header. On large moderate yielding farms where the system includes barley, there are clear unquestionable advantages in the stripper system. Although the results are less clear on high yielding wheat farms, the faster workrate can result in a more favourable cost profile if the farmer takes full advantage of finishing earlier by burning or incorporating the straw, providing this takes no extra labour.

Threshing and header losses are an important component of the cost comparison between stripping and cutterbar headers. Conventionally one would expect a direct relationship between separating loss and straw throughput. The relatively little experimental evidence with the stripper suggests that is not strictly true, especially in wheat. Although the capacity of a combine and stripper header is higher in wheat crops, this is not proportional to the reduction in straw throughput. This information also has consequences for conventional advice on the height of cut with a cutterbar. Further experiments are needed to clarify this.

Forward speed has an effect on header losses with the stripper header. Speeds in excess of 7 km/h should be used to keep these at a low level. Header losses in standing versus laid crops also need further study with both types of header.

Three alternative whole crop harvesting proposals are analysed using a whole farm model on a 250 ha combinable crops farm and a 200 ha grass-cereal farm (half cereal). Land type was shown not to affect the comparisons.

The proposal for whole crop harvesting with drying and separation at the farmstead, leading to conventional dry grain for sale, produces a saving which allows a capital expenditure on the farmstead equipment of over £70,000. Estimates of the likely equipment needed suggest negligible difference in profit in the end on the cereal farm but a profit increase of £50/cereal ha on the mixed cereal/livestock farm.

The proposal for whole crop cereal silage preserved with urea and fed to cattle, is insufficiently profitable to pay for the increased transport costs on the cereal farm. On the mixed cereal/livestock farm profit increases by £50/ha, even after allowing for the purchase of bedding. Additional livestock will be needed.

The proposal for whole crop cereal preserved with urea and used for industrial purposes, is insufficiently profitable to pay for separation costs on the cereal farm. On the livestock farm profit is increased by £45/ha.

The results clearly show that the value of whole crop harvesting comes from the saving of the combine harvester on a relatively small cereal area on which a forage harvester is already available plus the availability of adjacent livestock. Transport costs are the major disadvantage. A 25% error in estimates of value was sufficient to eliminate the savings. In particular reducing the value of whole crop cereal silage from £80.8/t to £77.2/t.

Lack of information compounds the problem of variability when making comparisons. Predictive systematic estimates of straw intake by cattle are almost negligible in spite of a considerable quantity of experimental measurements. The value of straw or whole crop silage depends on the feed value and intake of straw. A change in value of only £3/t can make or break the profitability. Grain losses when combining are only well studied for wheat, barley and oats. More information is needed on shedding, header and threshing losses in crops such as oilseed rape, beans and peas. In all cases the need is for data suitable for system analysis rather than just comparative experiments.

Contents

An operational research study of the alternatives to the combine harvester

1. Introduction

The combine harvester has become the only way of harvesting cereals. It has a large number of advantages not least that it is highly developed and can harvest most arable seed crops well. To improve on the system, alternatives must concentrate on exploiting the disadvantages of the combine. What are these and how can they be improved upon:

a. **Capital cost.** A combine is very expensive. The best a small farmer can do is to buy secondhand or use a contractor. Considerable savings could be made if the size needed was reduced or if a cheaper machine was used.

b. **Grain moisture content.** The combine can only work if the grain and straw are sufficiently dry. The grain must be dried for storage. Much time is lost waiting for the grain to dry. A weather independent system would be better.

c. **Grain losses.** After morphological ripeness, dry matter is gradually lost through respiration while waiting for the crop to be 'combine ripe'. In addition shedding losses due to wind, etc, increase. The cutterbar header causes grain losses which also increase with time. Not all the grain can be separated from the straw as it passes through the combine. An earlier start to the harvest would reduce losses as would reducing the combine straw intake.

d. **Straw.** Straw passing through the combine causes grain losses. The more straw, the greater the loss. If the farmer does not want the straw, why pass any through the combine. If the farmer wants as much straw as possible for feed or bedding, passing it through the combine maximises his grain losses. The straw is then placed close to the ground which makes it difficult to dry. The feed value in the chaff and leaf fragments will be lost as they cannot be picked up. Reducing the straw intake would reduce grain losses. An alternative method of harvesting the straw could eliminate straw losses.

Methods of exploiting these disadvantages to produce a better method of cereal harvesting are:

Proposal A - Grain Stripper Header : Use the grain stripper header instead of a conventional cutterbar.

This primarily attacks the problem of the amount of straw passing through the combine. The remaining straw is left standing so there are drying advantages but most of the leaf and the chaff will not be harvestable unless it is collected from the rear of the combine. Harvesting can be carried out in damper conditions than with the cutterbar.

Proposal B - Dry Whole Crop Harvesting : Harvest the grain and straw when dry with a forage harvester and separate them at the farmstead.

This attacks the problem of grain and straw losses. In addition the harvester is much cheaper. A disadvantage is that separation equipment is needed at the farmstead which may be as expensive as the combine harvester.

Proposal C - Wet Whole Crop Harvesting for feed : Harvest the grain and straw and preserve with urea. Feed to cattle.

This replaces the need for drying and separation with the need for preservative storage. Harvest can be much earlier and so grain losses are reduced. The harvester is cheaper. Straw losses are eliminated and its feed value enhanced.

Proposal D - Wet Whole Crop Harvesting for industry : As proposal C but the grain and possibly the straw are used for industrial purposes.

This is similar to the above but suitable for cereal farms. Separation is now needed but its use can be spread over the year. A use for the straw must be found.

This report consists of a study of these systems. Section 2 calculates the value of straw with or without different fractions. Section 3 calculates the value of saving time at harvest, either by starting earlier or having a faster workrate. Section 4 examines grain losses and the value of the stripper header. Section 5 examines the economics of the whole crop harvesting alternatives.

2. Value of straw fractions

2.1 Introduction

Straw consists of leaf, leaf sheath, nodes, internodes, chaff and rachis. In a conventional harvest the chaff and much of the leaf is lost, whereas most of the stem which has the lowest feeding value is harvested. How much are the lost parts of the straw worth?

2.2 The data

The data is from two sources. Firstly Orskov(1) who gives the degradability of different straw fractions, the effect of degradability on intake and the straw fractions in wheat and barley. The latter is assumed to be straw before combining as it corresponds well with data on this from the second source. The second source is Staniforth(2) who gives the fractions in wheat before harvest, the fractions in wheat and barley in the bale and the protein and D-value of the straw fractions.

Orskov (personal communication) found no difference between the proportion of straw before and after the combine, which may indicate that the loss is very dependent on how brittle the leaf is at harvest or that much of the loss occurs at baling. Orskov also found no loss of chaff in harvesting oats.

Assuming that all the nodes, internodes, rachis and leaf sheaths are harvested, the proportion of leaf harvested can be calculated and it is assumed that all the 'rachis and chaff' harvested is rachis, in other words that no chaff is harvested. Metabolisable Energy (ME) is calculated from the formula $ME = 0.15 D$ where D is D-value.

Orskov's data clearly suggests that intake is proportional to degradability. Per unit of intake therefore, increasing the degradability increases the intake without affecting the intake of the rest of the ration, thereby increasing the energy consumed per unit of intake. The average 41h degradability of straw$^{(26)}$ of 43% was taken as the basis for intake and the effective energy value of the comparative feeds was calculated compared to its intake.

The monetary value of the straw was calculated from the formulae developed in Audsley$^{(3)}$ for fattening cattle. The average monetary value is given by: 12.7(ME) + 0.193(CP) - 63.4 £/tDM (ME in MJ/kgDM, CP in g/kgDM). Yields were assumed to be 5t/ha wheat and 3.5t/ha spring barley (= 4.25tDM/ha and 2.98tDM/ha respectively).

Three other items of data are relevant from Staniforth$^{(2)}$. He quotes the overall feeding value of wheat and barley straw from Alderman$^{(4)}$. The CP for wheat from 1975 range from 1.6 to 2.8% which is lower than that for any of the fractions in 1977's data used. The ME value is comparable. For barley the CP content is comparable but the ME value is considerably higher. However some Indian data shows the CP content ranging from 3.56 up to 5.63 in wheat. Another analysis of barley straw shows CP higher than the values used. Finally a large portion of the protein in wheat is insoluble (e.g. 2.0% in the leaves). On the plus side the formula indicates that CP has only a small effect on straw value. However it should be born in mind that these additional data suggest that, if anything, wheat is slightly overvalued and barley slightly undervalued in this analysis.

Finally the 'degradability' analysis suggests that the current price paid by farmers for wheat straw (£20-25/t versus £25-30/t for barley straw) is far higher than its feed value. There could be several reasons for this. (i) It is known that farmers will feed barley straw in preference to wheat straw and the wheat straw may actually be used for bedding; (ii) the difference in feed value is not readily apparent; (iii) market forces - below that price it is not worth baling, there is a surplus of baled straw so that prices in general do not rise above this base level, transport costs mean that even at this level barley straw is only just worth buying.

2.3 The Analysis

2.3.1 Winter Wheat

Winter Wheat straw contains:

	%	% in bale	CP g/kg	D-value	ME	Degradability in rumen (41h), %
Leaf Sheath	15.5	15.5	55	41	6.25	57.6
Leaf	18.4	4.2				
Internodes	46.5	46.5	25	39	5.85	31.4
Nodes	5.7	5.7	36	38	5.70	48.3
Chaff	10.6	-	46	36	5.40	38.0
Rachis	3.2	3.2	37	36	5.40	48.3
	99.9	75.1				

These fractions can be combined in various ways as follows:

	% of total	CP,g/kg	ME	Degradability	Effective ME	Effective CP	Value £/tDM	% of baled weight
a) Baled straw	75.2	34.2	5.92	40.3	5.55	32.1	13.3	100
Lost fraction	24.8	51.2	5.89	49.2	6.74	58.6	33.5	33
b) Harvest all straw	100.0	38.4	5.91	42.5	5.84	38.0	18.1	133
c) Leaf, chaff, rachis	32.2	50.2	5.89	50.2	6.88	58.6	35.2	43
Remainder	67.8	32.8	5.93	38.8	5.35	29.6	10.3	57
d) Chaff only	10.6	46.0	5.40	38.0	4.77	40.7	5.1	14

Taking 5t/ha straw baled as the present yield, which is 4.25t DM/ha, the bales represent an income of £56.5/ha. Harvesting the lost fraction as well, either separately, as a whole (b) or as different parts (c) is worth an extra £47.0/ha and increases yield by 33% (1.7t/ha). Assuming <u>no extra</u> labour is required, this is equivalent to an extra machinery capital cost of £208/ha.

If the chaff was harvested separately, this is 0.7t/ha and is worth £3/ha.

2.3.2 Spring Barley

Spring barley straw contains:

	%	% in bale	CP g/kg	D-value	ME	Degradability in rumen (41h), %
Leaf Sheath	27.0	27.0	42	53	7.95	71
Leaf	18.1	4.2				
Internodes	44.6	44.6	15	30	4.50	40
Nodes	5.7	5.7	27	39	5.85	56
Chaff	3.0	-	28	45	6.75	56
Rachis	1.5	1.5	34	42	6.30	56
	99.9	83.0				

These fractions can be combined in various ways as follows:

	% of total	CP,g/kg	ME	Degradability	Effective ME	Effective CP	Value £/tDM	% of baled weight
a) Baled straw	83.1	26.3	5.92	53.0	7.30	32.4	35.5	100
Lost fraction	16.9	39.5	7.74	68.3	12.29	62.7	104.8	20
b) Harvest all straw	100.0	28.5	6.23	55.6	8.06	36.9	46.0	120
c) Leaf, chaff, rachis	22.6	39.6	7.68	68.0	12.15	62.6	103.0	27
Remainder	77.4	25.3	5.80	52.0	70.01	30.6	31.6	93
d) Chaff only	3.0	28.0	6.75	56.0	8.95	36.5	57.3	4

Taking 3.5t/ha straw baled as the present yield, which is 2.98t DM/ha, the bales represent an income of £106/ha. Harvesting the lost fraction as well, either separately, as a whole (b) or as different parts (c) is worth an extra £62/ha and increases yield by 20% (0.7t/ha). The lost fraction is a good feed. Assuming no extra labour is required, this is equivalent to an extra machinery capital cost of £278/ha.

If the chaff was harvested, this is 0.13t/ha and is worth £7/ha.

2.4 Conclusion

The value of harvesting the fraction of straw lost in baling, in terms of the increased income from its use as cattle feed is:

		Income, £/ha	Yield, %
Winter Wheat Lost	Fraction	+ 34	+ 33
	Chaff	+ 5	+ 14
Spring Barley Lost	Fraction	+ 62	+ 20
	Chaff	+ 7	+ 4

The benefit in harvesting the lost fraction of wheat straw is due to more of the same, not a better product. The benefit in barley straw includes this effect but the leaf fraction represents a good feed on a par with hay.

3. The value of a combine harvester hour

3.1 Introduction

Consider a combine harvester which is more unreliable than an otherwise identical combine harvester. This could be for a large number of reasons but may be the age of the machine or an improved feature on the more reliable machine. Secondly, consider identical combine harvesters which are driven at different speeds or start harvest at different times so that the end of the harvest occurs at different times.

What is the value of the difference in terms of the effect on farm profit? Clearly there will be differences in the cost of the harvesting operation but there will also be differences in the cost of succeeding operations, for example, the timeliness of planting winter crops or the area of winter crops the farmer is able to plant.

When forward planning, a farmer makes an assumption as to the likely start of harvest and the likely workrate of his combine harvester. He uses these along with many other assumptions to decide on the labour, machinery and cropping which he expects will maximise his profits. This type of analysis can be achieved using the technique of *linear programming* but it is generally considered too complex and the more usual method is to make piecemeal decisions based on partial budgets.

In partial budgets, one attempts to identify the differences between similar systems and determine an associated cost. It is assumed that the rest of the farming system remains unchanged. However given an earlier end to the harvest, this is unlikely to be true. Selecting a faster combine will allow more time for cultivations and allow winter crops to be planted earlier. This will make it more profitable to plant a greater proportion of winter crops or more winter wheat than winter barley or employ fewer men. In order to continue to use a partial budgeting method, it is thus necessary to know the cost or value of this effect on the rest of the farm system.

Consider the following partial decisions:

1. What is the value of starting harvesting earlier (later)?
   This could occur in a decision between high temperature and near-ambient grain drying.
2. What is the value of harvesting at a faster (slower) workrate?
   This could occur by simply driving faster, using a stripper header, or having a larger combine but can also be due to improved reliability.

It is important to differentiate between the causes of these effects. In any particular year the weather will affect the time and speed of harvest and thus its cost and completion time. The purpose of this analysis is to <u>eliminate</u> this 'particular year' effect and determine the cost (or equivalently profit reduction) of more permanent changes in a typical year.

The consideration is whether the change is planned for. 'Planned for' means that the farming system is selected based on the information that the change exists - thus a slower workrate would lead to a larger combine being purchased and possibly also larger tractors for cultivation. In the alternative unplanned case, the machinery has already been purchased and a later end to the harvest means the next crop must inevitably be planted later or contractors employed.

The method of analysis is to use a comprehensive linear programming model of an arable farm to determine the effect on profits from changes to the combine harvester system. The results will then be used in four example partial budgeting exercises:

1. The optimum replacement interval for a combine
2. The optimum speed for combining
3. A comparison of high temperature and near-ambient grain drying
4. A comparison of a grain stripper header and a conventional header.

3.2 The model

The basic linear programming model has been described by Audsley[5]. The modelling system commences from a database containing details of a wide range of crops, operations and machinery. The required crops are selected from this database and the sizes of the key machines are specified. The details of the operations and their workrate, the machinery and their costs are then extracted and derived from the database.

For this study the farm selected was 250 ha of medium land growing winter wheat, winter barley, oilseed rape and spring beans. The tractors owned by the farm would be either 60, 100 or 140 kW. The farm has one combine harvester of 7, 9, 11, 13, 15 t/h nominal overall capacity. All the other details of the farm are listed in full in Appendix 1.

The key elements for the study are the workrates of the combine harvester in each crop. For cereals these are proportional to the yield of the crop but for other crops they are independent of yield. The workrates are specified for an 11 t/h combine and the workrate for other sizes is determined pro-rata.

Winter Wheat	(0.100 x yield of wheat) h/ha
Winter Barley	(0.112 x yield of barley) h/ha
Oilseed Rape	1.53 h/ha
Spring Beans	1.53 h/ha

Changing the size of tractor on the farm, changes the workrate of the power critical jobs pro-rata. Thus, for example, ploughing using a 60 kW tractor and a 3-furrow plough at 2.38 h/ha becomes ploughing using a 140 kW and 7-furrow plough at 1.02 h/ha. It is possible to specify a fixed number of a type of machinery if required.

In each case the optimum solution for the given data and constraints was obtained. This was the cropping, labour and machinery which gave the maximum profit. An example of a full solution is given in Appendix 2. Generally only the profit figure is required for this analysis. It is however worth noting here that the effects of a change in the data are frequently complex and cannot be predicted, although in retrospect rational explanations can usually be suggested. To take an example consider the marginal value of oilseed rape which is the amount by which the price has to fall to cause a change to the solution or equally the value of growing one extra hectare of oilseed rape.

Consider increasing the gross margin of winter wheat (eg. higher yielding varieties). Clearly this will increase the attractiveness of wheat and thus reduce the attractiveness of the other crops and thus the marginal value of oilseed rape will fall.

Incorrect. Solving the model gives a substantial increase in the marginal value of oilseed rape. The (retrospective) explanation is that winter wheat is now more valuable and one needs more break crops to allow more winter wheat to be grown. The 'pressure' to break the rotational constraint on oilseed rape and grow more is therefore increased.

3.3 Results

3.3.1 Unchanged, unconstrained

The first step was to obtain the farm profit with the basic data for the 15 combinations of combine and tractor sizes (the optimum is underlined):

Tractor size	Combine size				
	7	9	11	13	15
60	61114	63502	64191	64043	63502
100	56528	60288	61692	61889	61512
140	50816	55956	58224	58974	58930

The optimum tractor size was clearly 60 kW and the optimum combine size was 11 t/h. This solution requires one man per 100 ha, i.e. 2.5 men on this particular size of farm.

3.3.2 Unchanged, fixed labour and tractors

A fixed amount of labour (with the same number of tractors) would be expected to modify the optimum solution. The number was fixed at just below and just above the continuous optimum. The corresponding profits were:

	Tractor size	Combine size				
		7	9	11	13	15
2 men						
	60	-	-	-	-	-
	100	-	-	-	60801	60641
	140	-	-	54406	55848	55207
3 men						
	60	59958	61181	60343	59232	57842
	100	51252	51528	50696	49551	48005
	140	42283	42099	41437	40118	38654

With 2 men it was only possible to crop the whole area in the cases given. The optimum was to use 3 men with the next smaller size of combine. There was little difference in profit from the two man solution using the next larger size of combine and tractor.

3.3.3 Earlier harvest

In any particular year, the cereal harvest can be earlier or later depending mainly on the weather. This, however, is not under the farmer's control and in strategic planning it is only possible to consider a typical start time for the harvest.

There are a number of factors that are under the control of the farmer and enable the start of harvest to be moved earlier or later. One obvious example is the method of grain storage. Near ambient grain-drying requires the grain to reach 20% mc or less whereas high temperature grain drying allows harvest to start at a higher moisture content. Preservative methods of storage could allow an even earlier start. Other reasons for an earlier start to harvest are the selection of variety or earlier planting.

The start of harvesting in the basic system was moved 1 and 2 weeks earlier and later and the new optimum farming systems determined for the unconstrained case and for 2 and 3 men. The harvest workrate was unchanged so that the end of harvest changed by the same amount.

	Tractor	Combine	Start of harvesting, weeks				
			-2	-1	0	+1	+2
	60	9	68175	66404	63502	60887	58405
		11	68808	66950	64191	61587	59335
		13	68588	66729	64043	61519	59351
	100	9	65735	63583	60288	57703	54363
		11	66675	64779	61692	59170	56114
		13	66657	64845	61889	59441	56659
2 men							
	100	9	62940	-	-	-	-
		11	64962	63487	-	-	-
		13	64307	63940	60801	-	-
3 men							
	60	9	63268	62798	61181	60410	57376
		11	62444	61927	60343	59928	58255
		13	61094	60577	59232	58902	57286

The optimum size of combine and tractor remains unchanged except for the extreme two week changes. With the two week later harvest it is just better to use the next larger size of combine. The value of starting harvest earlier or later is:

	Tractor	Combine	2 weeks earlier	1 week earlier	1 week later	2 weeks later
	60	9	4673	2902	-2615	-5097
		11	4617	2759	-2604	-4856
		13	4545	2686	-2524	-4692
	100	9	5447	3295	-2585	-5925
		11	4983	3087	-2522	-5578
		13	4768	2956	-2448	-5230
2 men						
	100	13	3506	3139	-	-
3 men						
	60	9	2087	1617	-771	-3805
		11	2101	1584	-415	-2088
		13	1862	1345	-330	-1946

The value is not affected very much by the size of the machinery and there is little error in using the optimal sizes to predict the effect for all sizes. The effect is slightly non-linear, being a little less than twice the change for two weeks compared to one week. One might have expected later harvesting to cost more than the corresponding benefit from earlier harvesting but in fact the differences are small and can be neglected.

With a fixed number of men and tractors, the effects are less stable across different sizes and weeks as it depends how close to critical the fixed number actually is. Thus with 3 men, the disadvantage of a later harvest is very much less as there is ample surplus labour anyway. Only with the smallest sizes and a two week later harvest does the cost begin to approach the unconstrained case as labour becomes critical. The advantages of an earlier harvest are also less. With 2 men, the system was only always feasible with the largest machinery and the savings with earlier harvesting are high. In some of the other cases, not listed, the savings are extremely high as the system changes from being feasible to non-feasible or vice-versa, of the order of £6000 for a week. It has little affect on the optimum system however. Clearly, however, the savings are a function of the particular farm and could be more or less for a slightly different farm area, soil type or annual rainfall. It is thus safer to use the unconstrained solution to get an overall estimate of the effect.

Thus in a partial budget comparing systems of harvesting, one of which allowed a start one week earlier, there would be an additional knock-on affect on the profitability of the whole farming system of about £2700/week. This is £10.8/ha or taking an average yield of £8t/ha, £1.35/t per week.

Example

Consider a high temperature drier costing £40,000, replaced after 15 years and drying the equivalent of 1500 t wheat per year. Harvest starts at 25% m.c. and the average drying required is from 21% to 14%. The cost of drying is £5.72/t(6) made up of £3.49 for machinery and £2.23 for fuel.

Compare this with a near ambient grain drier costing £40/t storage capacity, depreciated over 40 years. Harvest starts at 20% m.c. and the average drying required is from 18 to 14%. The cost of the drier is £2.89/t. Drying typically costs £1.96/t depending on the year and the control strategy employed(7). Total cost is £4.85/t.

This partial budget indicates that in this case the near ambient drier is clearly preferable to the high temperature drier. Allowing £2700 for a week earlier start however, reduces the high temperature cost to £3.92/t, clearly better than the near ambient drier.

3.3.4 Faster harvest

The speed at which the harvest is carried out can be affected by a number of things:

1. the speed chosen by the farmer to optimise the sum of threshing and shedding losses.
2. delays due to breakdowns which would be expected to gradually increase over the life of the combine and therefore slow down the harvest.
3. the option of using a stripper header, thereby reducing the straw throughput and allowing a higher workrate for the same level of threshing losses.
4. the proportion of the crops that are lodged.

In as much as the effects can be predicted from year to year, the farm system will have been optimised. Thus although breakdowns are random, the farmer will have an idea of the likely level based on the last few years. Similarly with lodging, the farmer will know from past experience (which includes the level of nitrogen he tends to apply) how much of the crop will be lodged and thus slow up harvest. He will have adjusted the farm system accordingly. In any particular year the situation with regard to breakdowns and lodging might actually be better or worse but the strategic plan is designed to optimise an average amount.

The change in the optimum due to each factor can be interpreted as a cost/benefit due to a higher/lower level of breakdowns, etc. For breakdowns, an alternative would be to purchase a new machine with a lower level of breakdowns provided the cost, that is effect on the long-term profit, is less than the cost of coping with the old machine's level of breakdowns. For lodging, an alternative would be to apply less nitrogen, providing the overall reduction in yield and thus profit was less than the cost due to the lodging.

Three separate situations can be identified for which optimum systems will be altered.

(i) increasing combine workrate by increasing the combine speed thereby increasing threshing losses.
(ii) increasing combine workrate without changing threshing losses (e.g. breakdowns)
(iii) increasing combine workrate in cereals only without changing threshing losses (e.g. stripper header).

3.3.4.1 Increasing speed/increased losses

From the threshing loss equations (see Section 4.3), it can be calculated that, near the optimum, changing the speed of the combine by 10% changes the cost of threshing losses by about £5/ha. The overall change in shedding losses is negligible for this small change. The optimum farm systems are:

		+10%, +£5/ha			-10%, -£5/ha		
Tractor	Combine	Profit	h saved	Benefit/h	Profit	h extra	Cost/h
60	9	63935	34	13	62578	34	27
	11	64378	28	7	63553	28	23
	13	64149	23	5	63616	23	19
100	9	61080	34	23	58861	34	42
	11	62116	28	15	60704	28	35
	13	62119	23	10	61268	23	27

That there is any saving at all from increasing the speed suggests that the combine should be going faster in any case to be optimal. If it is assumed that the original is the optimum, then the results can be used to calculate that threshing losses must increase due to the faster speed by more than 6.8, 5.8, 5.5, 8.1, 6.7, 5.9 £/ha respectively.

Reducing the speed in order to save £5/ha is not worthwhile and cost £20-£40/h. The level of reduction in threshing losses needed to justify this reduction in speed is 8.7, 7.6, 6.7, 10.7, 8.9, 7.5 £/ha respectively.

The results show the smaller combine should be going relatively faster for its size, which is perhaps to be expected. However, the difference caused by the tractor size is even greater. On a farm with large tractors the combine should be going faster than on a farm with small tractors with the same size of combine.

3.3.4.2 Increased workrate in all crops

Increased workrate in all crops without increased losses refers basically to reducing the amount of non-working time such as the time lost due to breakdowns and the time needed to effect a repair. It could however equally refer to a comparison between machines where one was capable of a higher throughput for the same level of threshing losses.

The change in the farm profit for every hour gained or lost, £/h, is:

Tractor	Combine	-10% workrate	+10% workrate
60	9	65	50
	11	68	52
	13	72	58
100	9	80	60
	11	82	60
	13	81	62

The value is fairly insensitive to both size of combine and size of tractor but is clearly non-linear, being significantly greater per hour lost than per hour gained.

Example: Replacement interval for combine

How does this affect the replacement interval for a combine harvester? Listed below is the typical discounted cash flow calculation of the replacement interval for a £60,000 combine(8):

Year	Repair cost	Annual Cost	
1	718	17724	
2	1782	15818	
3	2944	14776	
4	4166	14088	
5	5431	13624	
6	6730	13324	
7	8057	13152	
8	9409	13082	←---------- optimum
9	10781	13094	
10	12171	13173	

The increasing repair costs, result in an optimum replacement interval of 8 years.

Unfortunately little data exists on the amount of time spent on breakdowns and repairs from which to calculate the reduction in combine workrate due to breakdowns. Assume that 10% of the harvesting time is spent on non-routine repairs by a 5 year old combine and that the time spent is proportional to the repair cost for other ages. This can be converted to a cost using the above £68/h lost.

Year	Repair cost	Hours lost	Cost/year	Revised annual cost	
				(a)	(b)
1	718	3.7	-1635	16089	16905
2	1782	9.1	-1266	14363	14782
3	2944	15.0	- 863	13508	13795
4	4166	21.2	- 439	13011	13231
5	5431	27.7	0	12740	12921
6	6730	34.3	345	12618	12773
7	8057	41.1	697	12615	12751
8	9409	48.0	1055	12709	12831
9	10781	55.0	1419	12879	12991
10	12171	62.1	1788	13113	13216

Column (a) shows the effect of including these costs in the annual cost calculation. The method suggests few hours are lost in the first year although in practice the reason for the low cost could be the first year warranty. The effect of an extra 12 hours lost in the first year of owning the machine is shown in the annual cost column (b).

In all cases the effect on the replacement interval is small, only reducing the optimum from 8 years to 7 years. The penalty for early replacement has been reduced - for example replacing after 4 years cost £1000 originally but taking into account a 10% repair time reduces this cost to £480. Note however that the actual level of hours lost due to unreliability is at present unknown.

Example: Improved combine controls

What is the value of improved control features which allow the combine to be driven faster? These would be features that took away from the driver some of the load of continual adjustments to reel, cutterbar height, forward speed, etc., allowing him to concentrate on more 'major' decisions and thus drive a little faster, particularly in difficult conditions. They might also reduce combine down-time, for example, less cutterbar damage, less broken fingers to replace, by more rapid automatic adjustment. Suppose the workrate was increased by 10%. The total saving per year would amount to £1440 with the 11 t/h combine. The amount that could be justifiably spent on an improved control system for this size of combine is thus £8167 (assuming a 7 year replacement interval).

3.3.4.3 Increased workrate in cereals only

By employing a grain stripper header on the combine, it is possible to increase forward speed without increasing threshing losses in cereals. The advantage does not carry over to some of the other traditional combinable break crops such as oilseed rape and beans for which a conventional cutterbar is better. Experiments have shown that threshing losses are not reduced pro-rata with straw throughput so that speed cannot be increased as much as conventional wisdom that losses are proportional to straw throughput would have indicated. There may also be increased header losses. The value of increasing the workrate in cereals only was calculated; £/h.

Tractor	Combine	+10% speed	+20% speed	+10% speed,+£5/ha cost
60	9	65	55	12
	11	64	57	1
	13	71	63	6
100	9	79	68	25
	11	79	68	13
	13	84	73	6

Increasing the speed saves about £70/h over the first 10%, but a 20% increase is only worth about £60/h; the saving being more with the larger size of tractor. Thus for the 11 t/h combine, if the stripper gave an increase in speed of 20% with no increased losses, the annual cost which would be justified on the stripper header would be £3158. This corresponds to a capital cost for the stripper, based on a 7 year replacement interval and 5% annual maintenance cost of £13954. (£17911 with zero maintenance cost).

If, however, 10% increased speed is associated with an increased header loss of £5/ha, then the benefit is almost cancelled out and thus very little expenditure can be justified.

3.3.4.4 Land type

The above calculations have all been carried out on a medium land farm. The benefit comes from earlier planting or the need to employ fewer men and machinery to achieve the desired planting date. This would suggest that on heavy land where there are fewer hours available for planting, the benefit of extra time available in the autumn would be greater and vice-versa on light land. The farm gross margins for a sample of situations is:

	Land type		
	Light	Medium	Heavy
Combine Workrate			
normal	68355	64191	57181
+10% all + £5/ha	68550	64378	57376
-10% all - £5/ha	67718	63553	56517
+10% cereals	69072	64866	57861
-10% cereals	67401	63478	56277

The corresponding savings per hour are:

	Light	Medium	Heavy
+10% all + £5/ha	7	7	7
-10% all - £5/ha	23	23	24
+10% cereals	68	64	65
-10% cereals	91	89	86

Clearly land type does not affect the savings from changing combine speed, even though the cropping, men, machinery and profitability of the farms are significantly different. In fact, although the differences are small, it seems that the effect on light land is greater than on heavy land. The explanation presumably is due to the change being a larger percentage of the total workforce.

Note, however, that the crops available to the farms were unchanged. It is likely that a light land farm would also be growing some root crops, though it is not clear that this would have an effect on the calculated saving.

3.4 Conclusions

The knock-on benefit or cost of changes to the harvest system in terms which can be used in partial budgeting exercises is

	Possible Cause	+/earlier	-/later
Start of harvest, 1 week	Grain drying	£11/ha	£10/ha
2 weeks		£18/ha	£19/ha
Workrate, 10%	Reliability	£52/h	£68/h
Workrate in cereals, 10%	Grain stripper	£64/h	-
20%		£57/h	-

The results are not affected by land type. Only extreme changes alter the optimum size of tractor and combine. Considering specific farms and numbers of men and machinery gives either lower or higher savings depending on the circumstance. For example the value of starting harvest 1 week earlier was either £6/ha or £13/ha depending whether 2 or 3 men were employed.

4. The economic consequences of the grain stripper header

4.1 Introduction

In order to consider the potential benefits of using a stripper header, a detailed study was made of the comparative profitability of this harvesting system compared with that of the conventional cutterbar machine. Essentially the difference between the two is the way in which they deal with the straw portion of the crop. Whereas the cutterbar header cuts the straw and feeds it into the threshing and separating mechanism together with the grain, stripper header strips the grain from the straw and leaves approximately 70 to 80% of the straw in the field. Thus the amount of straw that is processed, is considerably reduced.

In operation, the stripper header offers a significantly higher grain throughput since the volume of straw passing through the machine is considerably less and thus the combine's separating mechanism does not become overloaded until a higher grain throughput(9,10) is reached. For the same width of header and threshing loss, the combine can travel faster. This in turn reduces the shedding losses(11), since the harvest is completed earlier, and equally increases the time available in the autumn for post-harvest activities.

The disadvantages might be its extra cost, since farmers might regard the header as an accessory (a complement to a conventional header), its increased power consumption although within the capacity of any combine that can be equipped with a maize header and increased header losses in some crop conditions (but also lower in some others). A few crops cannot be successfully harvested with the stripper header, but others notably linseed and badly necked barley, give reduced losses and higher output.

The stripper leaves standing straw which has both advantages and disadvantages. This study, which only considers the harvesting system, makes two alternative and extreme assumptions about this straw:

a) That the time saved by faster harvesting is equal to the extra time needed to dispose of the straw
b) That no extra time is needed to dispose of the straw.

In practice the alternatives are: burning or ploughing in the standing straw which is equivalent to b); chopping and spreading the straw, which is likely to take a little longer; and baling which will require an extra mowing operation.

In essence this study attempts to quantify harvesting losses and from these statistics, determine whether the total cost of harvesting with the stripper header, with its higher output, is more cost effective than with the slower cutterbar header.

4.2 List of variables and parameters

a = constant in fitted equations
a_i = area of ith crop
a_{ik} = limiting crop which can be processed in a day (hectares)
A = lower portion of straw
b = constant in fitted equations

B = upper portion of straw
B_A = capacity of bulk wet store
B_F = fixed cost of bulk wet store
B_u = cost per unit volume of the bulk wet store
c = constant in fitted equations
C_F = annual fixed cost of combining
C_V = variable cost of harvesting
C_x = initial capital cost (x = c combine with cutterbar, h header only, Σ combine + header)
d = constant in fitted equations
D = days since morphological ripeness
D_C = purchase price of drier
D_F = annual fixed cost of drier
D_V = annual variable cost of drier
f_c = cost of fuel for combine, £/l
f_e = field efficiency
f_d = cost of fuel for drier, £/l
F = fuel cost, £/h
G_L = cost of grain that is left in the field
h_k = time available for combining on day k, h
H = annual combine utilisation (hours)
H_d = total hours drying
H_{Li} = hours spent harvesting ith laid crop
H_{Ni} = hours spent harvesting the ith unlaid crop
i = index of crops
j = index of machine type (1 = cutter-bar, 2 = stripper header)
k = index of day
L_{HX} = header loss as a percentage of yield (X = C conventional, S stripper)
$L_{H\Sigma}$ = total cost of header losses in a particular harvest
L_S = shedding loss as a percentage of yield
$L_{S\Sigma}$ = total cost of shedding losses in a particular harvest
L_T = threshing loss as a percentage of yield
$L_{T\Sigma}$ = total cost of threshing losses in a particular harvest
n = number of crops
p = proportional effect of stripper straw on threshing losses
p_d = discount factor
p_{Li} = proportion of laid or necked crops in total crop area
r = rotor diameter, m
R_k = rainfall on day k
s = speed, km/h
s_t = specific straw throughput in tonnes of straw per hour per square metre
S = straw walker area of the combine, m^2
T = total annual cost of combine harvesting
T_d = total duration of harvest
t_g = throughput of grain, t/h
V_i = crop value, £/t
w_i = work rate of combine in ith crop, ha/h
W = wage cost, £/h
W_X = width of header, m (X = P predicted, A actual, S stripper)
y_i = yield of ith crop
Z_i = area of land ultimately harvested
Z_n = cumulative rainfall status on day n

4.3 The model of the harvesting system

The model is a development of a previous study by Audsley(8,12). Grain loss equations have been added for each type of crop and for different machines, and the specification of the combine harvester has been altered.

The model consists of a simulation of the combine harvesting operation for a sequence of crops during which the costs of operating the machine and the costs of lost grain from shedding, header and threshing are accumulated. Weather dependence is included by assuming that the decision to work or not on any particular day is determined by the rainfall over that day and the previous day (see the workability criterion ref 12). After harvesting, any wet grain is dried by a high temperature grain drier. The remainder of this section explains in detail the form of the model.

Within the model the shedding loss process commences immediately following morphological ripeness and continues until the crop is harvested. Morphological ripeness is defined to be when the grain moisture content is thirty percent. For example ten days after ripeness occurs, the yield of any harvested area of land will have been reduced by however much the cumulative shedding-loss function suggests. The longer the period of time that the crop is standing, the greater these losses are.

Where combine speed and rated capacity were used in the previous study(12), straw/grain throughput and straw walker area are now employed. It is assumed that the farmer drives his combine according to a pre-determined decision about what level of threshing loss is acceptable. The driver can monitor this loss from within the cab of the combine with grain loss sensors, and at this chosen loss level a particular grain throughput will be achieved.

The model utilises a different fitted curve for each distinct process, ie shedding, header and threshing losses, for each crop, and distinguishes between the stripper and the cutterbar headers in the case of both header and threshing losses. In this way the contrasting properties of the various machines and crops are reflected.

The model takes "the machine's ability to thresh" into account by referring to straw throughput and calculating specific throughput. In this way all machines of differing capacities can be described by the same curve. With the exception of header losses with the stripper header, the model makes the assumption that header loss is determined purely by how long the crop has been standing in the field since ripeness.

The model incorporates a formula linking the anticipated cost of the complete harvester to the size of its straw walker area. Likewise from these statistics, the predicted width of the cutter bar is calculated. In the case of the working combine possessing a larger than expected cutter bar the cost of the complete machine is increased by an appropriate amount. Prices are projected to October 1989 and combine statistics are taken from ref 13. The user can also specify a particular combine with a known cost and a known straw walker area. The model can thus commence either with information about the straw walker area or the cost of the whole machine, or both.

4.3.1 Crop data

Experimental data was assembled from a range of crops for shedding, header and threshing losses for all machines for which data was available. The following table identifies that which is (y), and is not (n) present.

Crop	Threshing loss		Shedding loss	Header loss	
	Cutterbar	Stripper		Cutterbar	Stripper
Wheat	y	y	y	y	y
Barley	y	y	y	y	y
Oats	y	y	y	y	y
Oil seed rape	y	n	n	n	n
Field Beans	y	n	n	n	n

It is evident from the above table that only wheat, barley and oats can be fully examined by the model since the other crops are lacking data covering shedding and header losses.

4.3.1.1 Curve fitting

Data on shedding loss, header loss and threshing loss was used to find curves of best fit for both cutterbar and stripper headers. The functions produced were then used in the model.

Statistical censoring is a problem with threshing loss data since when a test run produces unacceptably high grain losses further runs at higher throughputs will not be carried out. The implications are that the available measured data points at the higher levels of throughput do not reflect reality in that the high throughput/ridiculously high threshing loss data points are missing. Fig. 3b is a good illustration of the problem. The data appears to form three distinct curves. At a throughput of 4.5 $t/h/m^2$, data points are only available from one of the curves. When fitting a curve using normal regression techniques, this gives the false impression that even at high throughputs, low threshing losses pertain.

The data was either fitted conventionally using the best fit curve from the Maximum Likelihood Program or, in the case of threshing loss, fitted by minimising the perpendicular distance from a theoretically derived form of curve in order that the effect of censored data be reduced. The latter was achieved using a short program utilising a N.A.G. routine. It measures the perpendicular distance between each data point and a specified curve. Having calculated the total sum of squares, the program systematically adjusts the parameters in a manner that minimises this sum. When the program terminates it displays the vector of parameters that provide a best-fit curve.

In all cases, curves were selected on the basis of the lower the residual sum of squares the better the fit. It is important to note that even in the censored data case, which uses a user defined model, the residual sum of squares is still significantly less than the standard models of the Maximum Likelihood Program, and so can be justified on that basis alone. The following types of curves were used

Curve		Form
1.	Invert exponential (inv)	$y = a + b\exp(-c/x)$
2.	Linear plus exponential (lexp)	$y = a + b\exp(-cx) + dx$
3.	Composite exponential (dexp)	$y = a + (b + cx)\exp(-dx)$
4.	Logistic (log)	$y = a + b/(1 + \exp(c(x-d)))$
5.	Gompertz (gom)	$y = a + b\exp(-\exp(-b(x-m)))$
6.	Exponential (exp)	$y = a + b\exp(-cx)$
7.	Linear (lin)	$y = a + bx$
8.	Reference 12 (R12)	$y = a + bx + cx^d$

4.3.1.2 How the model deals with loss data

The simulation computes the grain losses each day from the variables such as crop type, specific throughput, and the number of days that have passed since morphological ripeness. For both shedding and header losses, losses depend on the day in which the crop is harvested and so for example if harvesting takes place on the twentieth day of harvest then shedding losses have been occurring in this area for twenty days plus the number of days before harvesting started that the crop was morphologically ripe. In the case of header losses, the crops propensity to be dislodged by the combine is an increasing functions of days. Once the specific straw throughput is known, a value for the threshing loss is calculated and this is used to describe losses which occur in any area of land that is subsequently harvested.

4.3.2 Grain loss costs

4.3.2.1 Shedding loss

Shedding loss is the loss of grain yield which occurs while the crop is standing untouched in the field. It includes not only visible loss due to wind and pests but also respiration losses. It is assumed that these influences are incorporated into the data by implication : the experimental data has been collected in real fields subject to all these influences and to attempt to model these complex factors would be needless and complicated and would result in double counting.

The development stage at which morphological ripeness is reached is taken as being the zero-loss-point, and from that day losses are accumulated. Shedding loss is determined by the crop type and the number of days since morphological ripeness that the crop has been standing. It is the average loss on each day and incorporates the losses due to gales, hail etc, as the expected loss each day, given the probability and amount of loss.

The shedding losses, L_s (Fig. 1a-c) are fitted as follows:
Barley $L_s = a + b\exp(-cD)$
Wheat $L_s = a + b\exp(-cD)$
Oats $L_s = a + b\exp(-cD) + dD$

Crop	Residual sum of square	Parameters				Model
		a	b	c	d	
Barley	0.051	-0.6374	0.6374	-0.02955	-	EXP
Wheat	15.025	12.48	-12.48	0.00654	-	EXP
Oats	43.62	-4.835	4.835	0.06927	0.328	LEXP

Shedding losses are independent of the machine used.

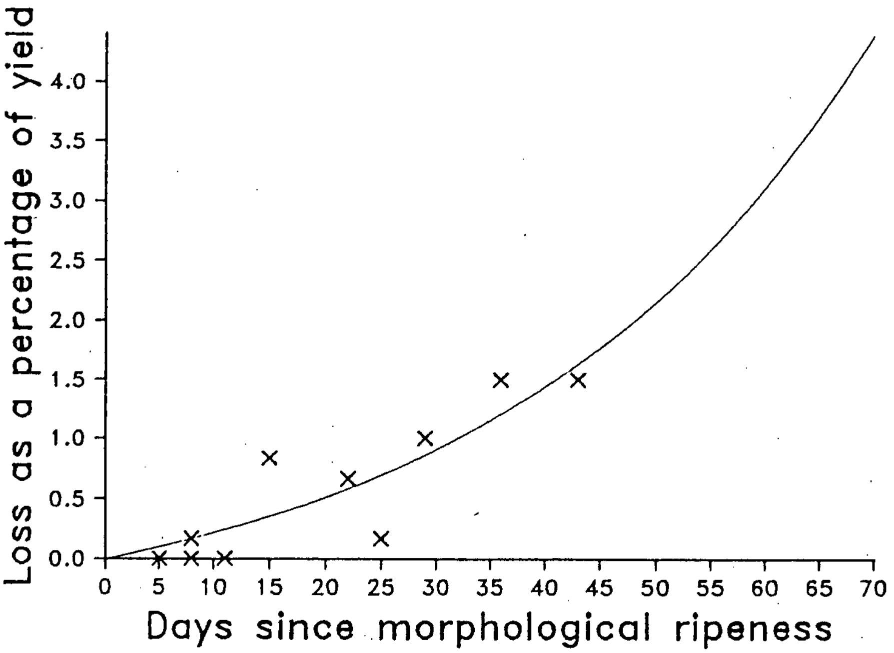


Fig. 1a Shedding losses relative to days since ripeness - barley

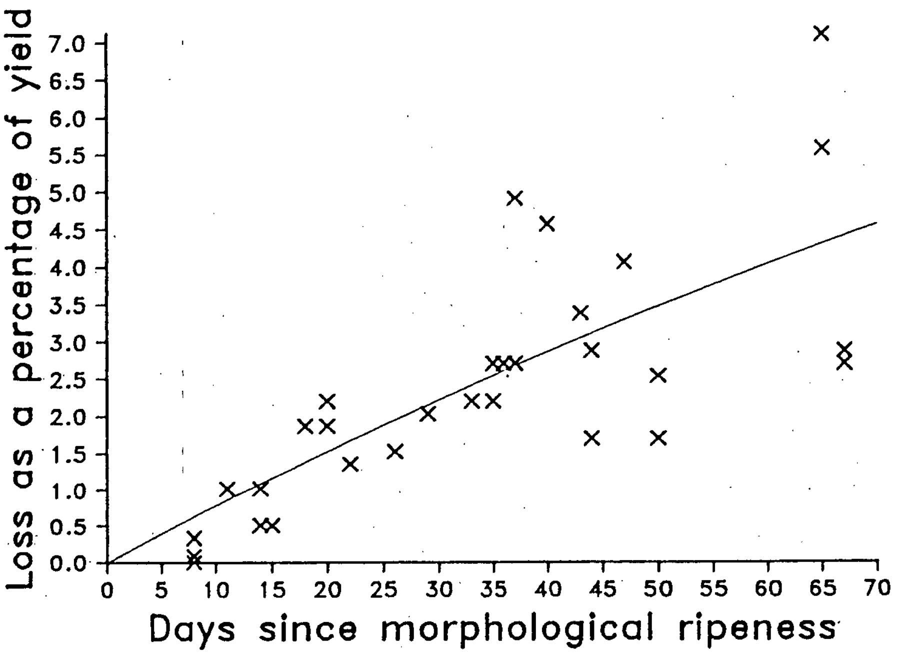


Fig. 1b Shedding losses relative to days since ripeness - wheat

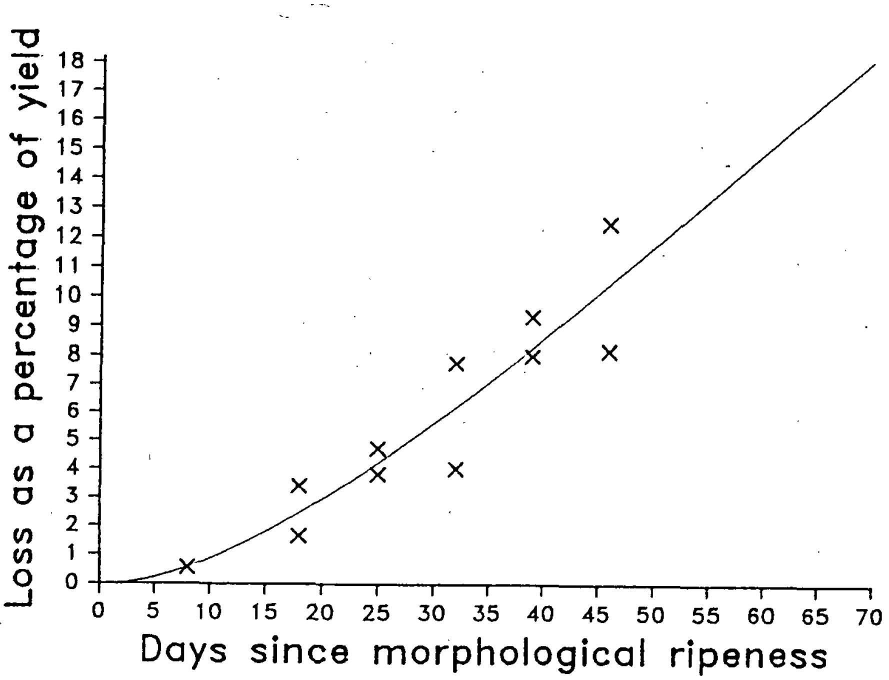


Fig. 1c Shedding losses relative to days since ripeness - oats

4.3.2.2 Header losses

Header losses are those losses that occur by virtue of the machine's passage through the crop. The action of the machine can dislodge some grain even before they are cut, and some of the crop that is cut falls outside or under the collecting area. Some crop is not cut. Such things as speed, the brittleness of the crop, and the type and width of header that the machine possesses are likely to influence losses. The width of the header may influence losses since observations have shown that the side of the header dislodges grains while harvesting is taking place. In the case of a narrow head, for any given size of field, there will have to be a larger number of passes than for a wide header and hence more occasions when grains are knocked off.

For a cutterbar header, it is assumed that over the range considered, width and forward speed have no effect on realised header loss. Therefore a fast combine, matched with a narrow header, will produce a similar pattern of header losses as a slow combine with a large header operated at the same work-rate. The extra edge loss has been ignored.

With a cutterbar header the number of days since morphological ripeness, and the crop type are taken as the explanatory variables of header losses and those other factors for which data is lacking are ignored. These hypotheses are supported by the header loss data where the passage of the days of the harvest already indicates gradually increasing crop losses. As in the case of threshing losses a family of curves is fitted for all the crops in which data are available (Fig. 2a-c).

Barley $L_{HC} = a + b \exp(-cD)$
Wheat $L_{HC} = a + bD$
Oats $L_{HC} = a + b \exp(-cD) + dD$

Crop	Residual sum of square	Parameters				Model
		a	b	c	d	
Barley	7.86	0.408	0.292	-0.062	-	EXP
Wheat	1.18	0.487	0.0347	-	-	LIN
Oats	0.519	-3.78	3.78	0.086	0.302	LEXP

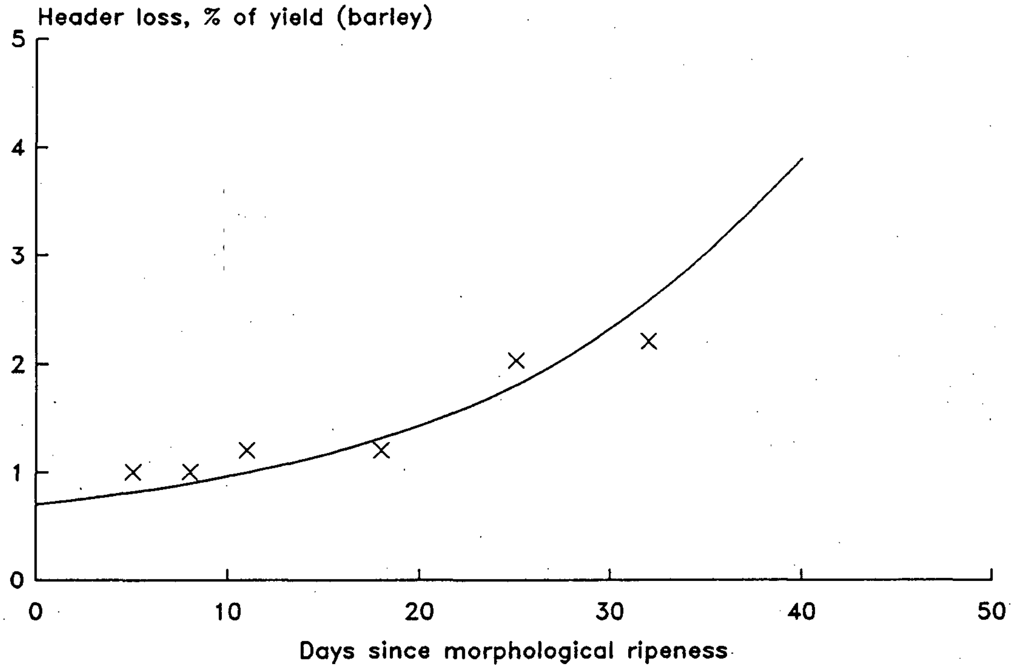


Fig. 2a Header losses relative to days since ripeness - barley

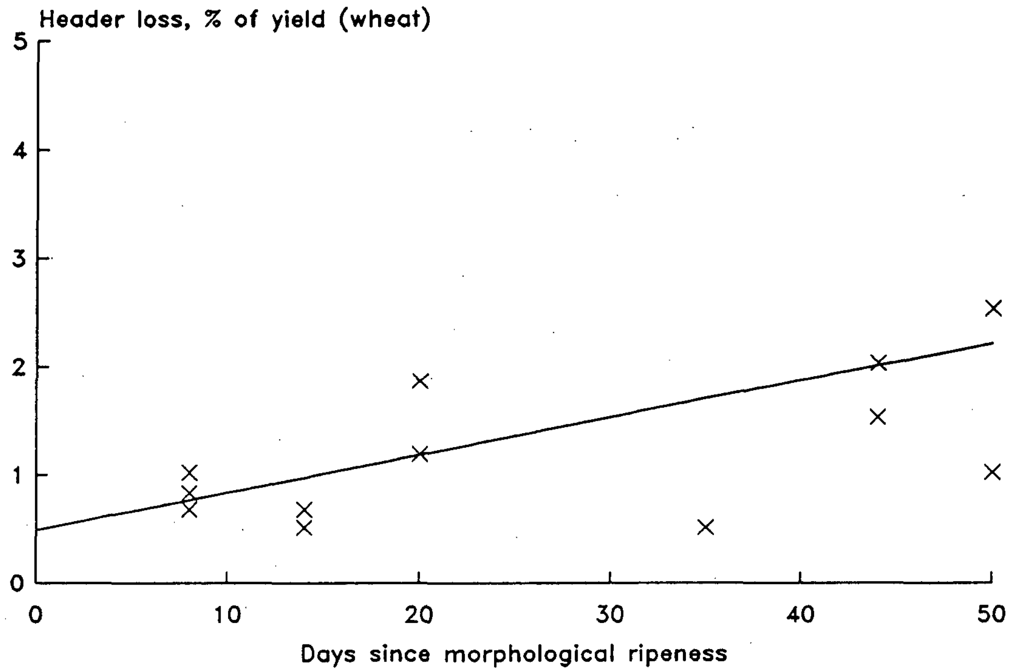


Fig. 2b Header losses relative to days since ripeness - wheat

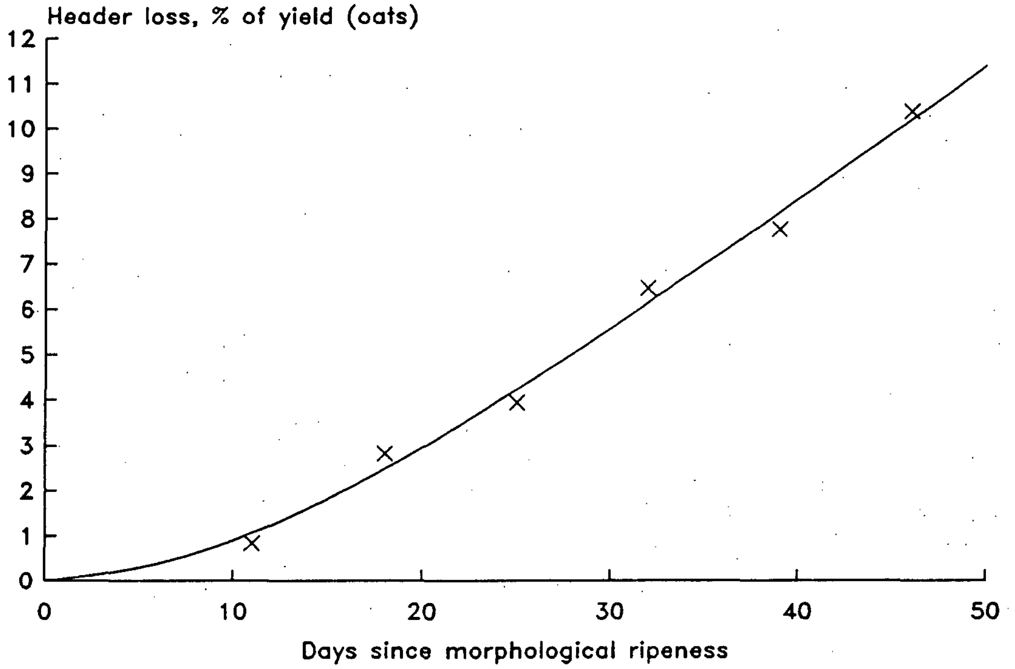


Fig. 2c Header losses relative to days since ripeness - oats

Where the crop is laid, or in the case of barley badly necked, losses will be much higher. The data suggests that a typical increase in the loss is 3.15% in both wheat and barley, though this is very much an average over a wide range of situations.

The stripper header is notably good at dealing with laid crops and it will be assumed that unlike the cutterbar header, losses are unchanged whether it is operating in laid/necked crops or not. Experimental data has shown the stripper header to produce an increase in header losses as the forward speed of the machine falls below 6 or 7 km/h but no reliable data exists on how the stripper header losses change with the passage of the harvesting season. The existing data on cutterbar header losses is used with the addition of extra terms to the equation to incorporate the speed effect.

$$\begin{aligned} L_{HS} &= L_{HC} + (3.32 - 0.348s) \quad \text{barley} \\ &= L_{HC} + (4.32 - 0.348s) \quad \text{wheat/oats} \end{aligned}$$

Thus whether the cutterbar or stripper has higher or lower header losses depends on the forward speed, crop type and whether the crop is laid/badly necked.

4.3.2.3 Threshing loss

Threshing loss is the increasing tendency of the combine to lose grain out of the back of the machine as the throughput rises. It is a function of straw throughput and separating capacity. Separating capacity of a machine(14,15,16) is determined by the straw walker area and is a measure of the machine's ability to separate the grain from the straw. For a given straw throughput a machine with a large separating area will produce a smaller threshing loss than a machine with a small area. A given size of separating mechanism has an upper limit to the straw(17,18) throughput that it can efficiently sustain (ceteris paribus) .

In the case of non-conventional separators,(19,20,21) like the axial flow and multi-cylinder models, where straw walkers are not present, other machine parameters which reflect the physical size of the separating operation (like rotor diameter and cylinder diameter) are referred to. These more recent innovations in separation techniques have attempted to address the problem of straw walkers becoming overloaded by the sheer volume of harvested material. These systems can also become overloaded and give high losses, but this usually occurs at a relatively higher rate of throughput.

Machine sizes are incorporated in the model by using specific throughput as the independent variable that drives threshing losses. This in the conventional case is defined as the straw throughput in tonnes per hour divided by the area of the straw walkers (in square metres). It is the straw throughput per square metre of straw walker area. Other factors which are likely to influence losses are the type of separator, the type of crop that the machine is processing, and the crop condition. The ratio of grain throughput to straw throughput in a conventional machine is assumed to be one.

Threshing losses are fitted to a theoretically derived curve (see Appendix 3):

$$L_T = a + b \exp(-c/s_t)$$

All crops utilise the same form of threshing loss curve for both the stripper and cutter bar header, but differ in the parameters that fit them. The parameters are given below. The curves for the straw walker machine are shown in Figs. 3-4 for an assumed grain straw ratio of 1.0

Straw walker combine with cutterbar header (fitted using NAG routines) : Figs. 3a-e

Crop	Residual sum of squares	Parameters			Model
		a	b	c	
Barley	73.89	0.691	55.4	7.93	INV
Wheat	7.06	0.315	96.8	11.57	INV
Oats	10.18	0.540	62.3	11.26	INV
Oilseed rape	0.49	0.886	10.9	6.73	INV
Beans	1.32	0.670	28.7	14.18	INV

Axial machine with cutterbar header (from ref. 13)

Crop	Model	Parameters			
		a	b	c	d
Barley	R12	0.09	0.08	1.27	-1.27
Wheat	R12	0.02	0.17	4.18	-1.48

Straw walker combine with stripper header: Figs 4a-c

Crop	Residual sum of square	Parameters			Model
		a	b	c	
Barley	0.0535	0.286	40.0	2.95	INV
Wheat	0.1223	0.535	43.7	3.23	INV
Oats	0.0909	0.370	14.9	2.52	INV

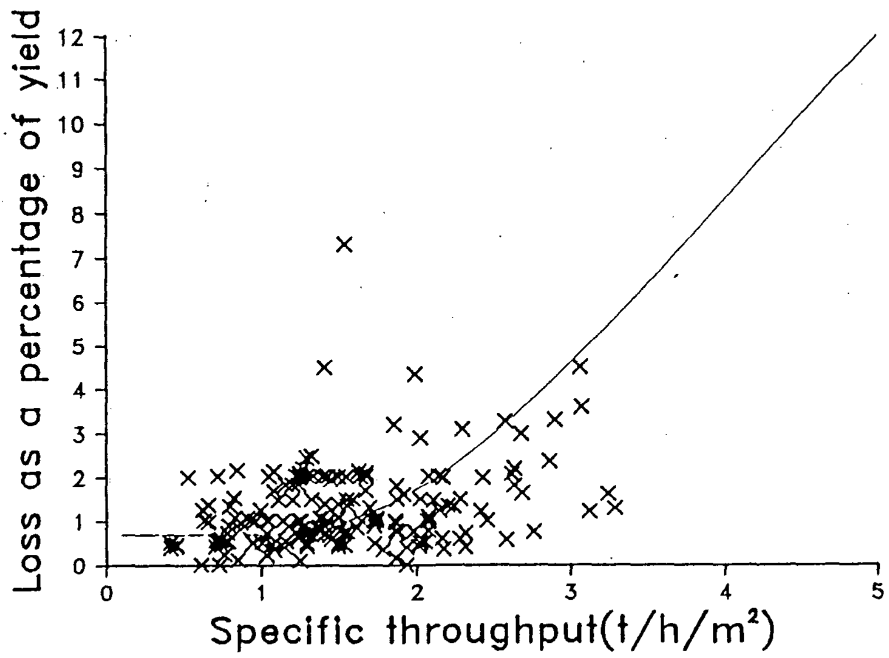


Fig. 3a Threshing loss as a function of specific grain throughput with a cutterbar header - barley

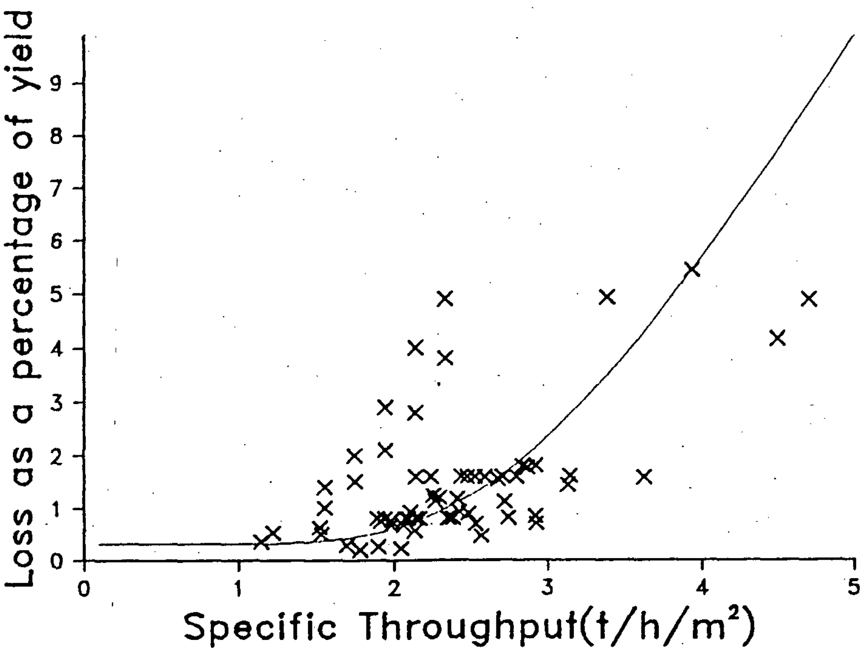


Fig. 3b Threshing loss as a function of specific grain throughput with a cutterbar header - wheat

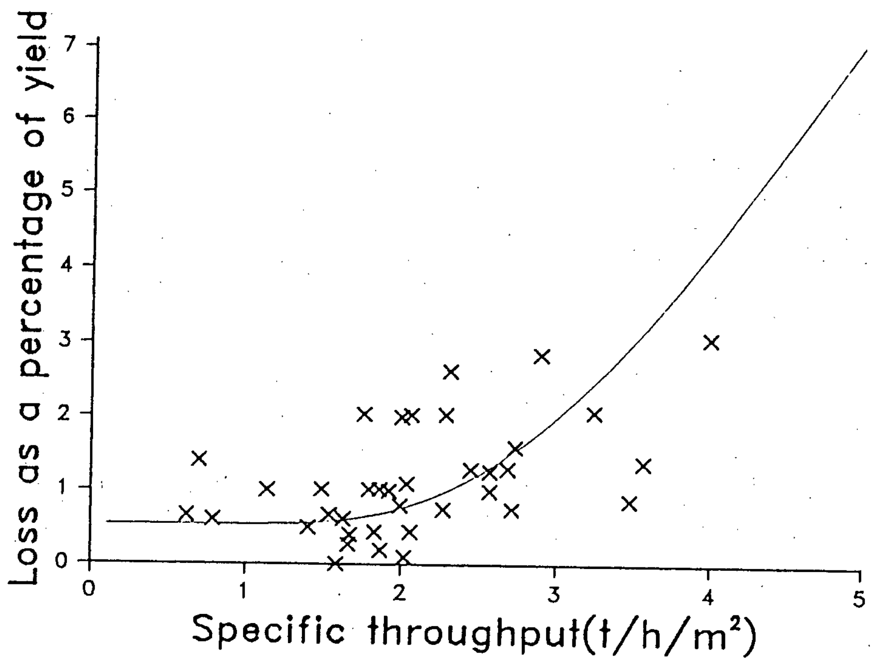


Fig. 3c Threshing loss as a function of specific grain throughput with a cutterbar header - oats

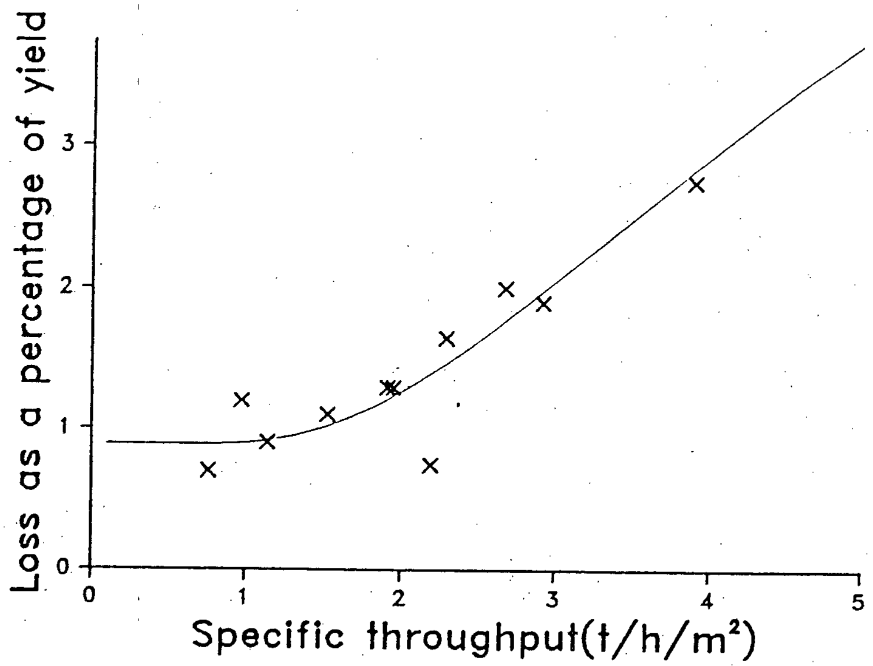


Fig. 3d Threshing loss as a function of specific grain throughput with a cutterbar header - oilseed rape

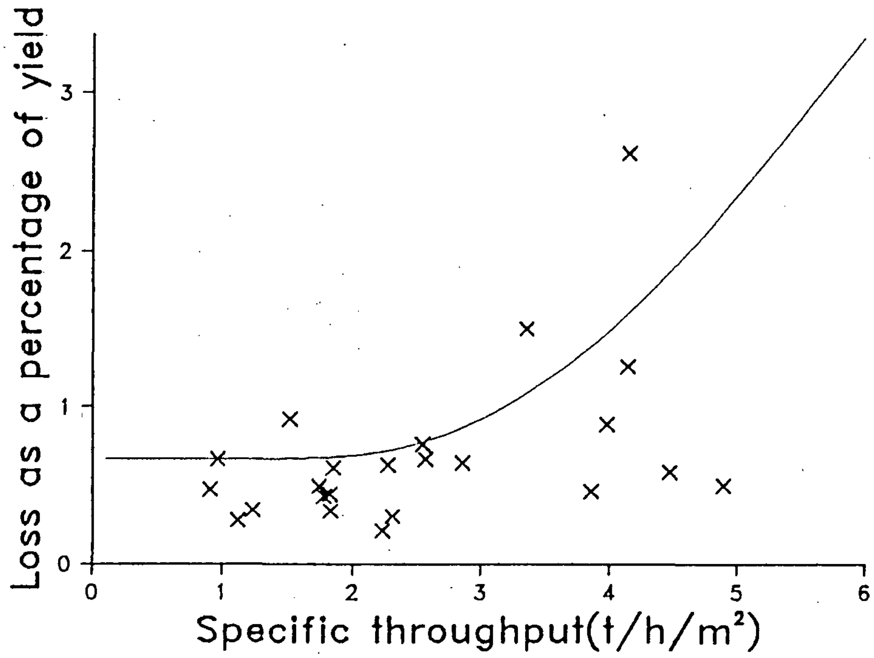


Fig. 3e Threshing loss as a function of specific grain throughput with a cutterbar header - beans

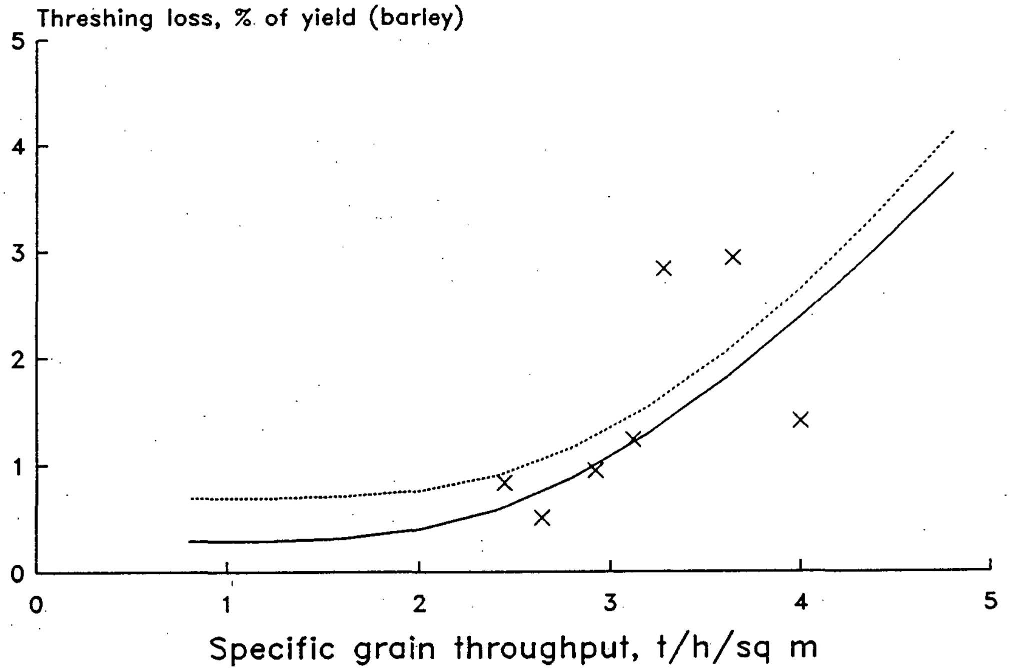


Fig. 4a Threshing loss as a function of specific grain throughput with a stripper header - barley
(—— fitted direct, ... fitted from cutterbar equation)

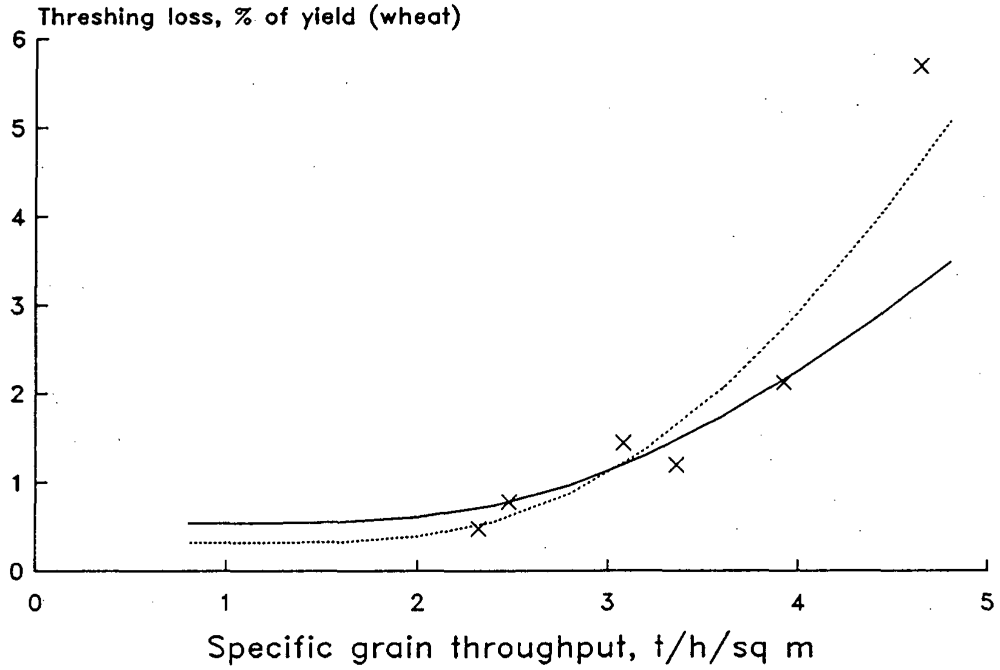


Fig. 4b Threshing loss as a function of specific grain throughput with a stripper header - wheat (—— fitted direct, ... fitted from cutterbar equation)

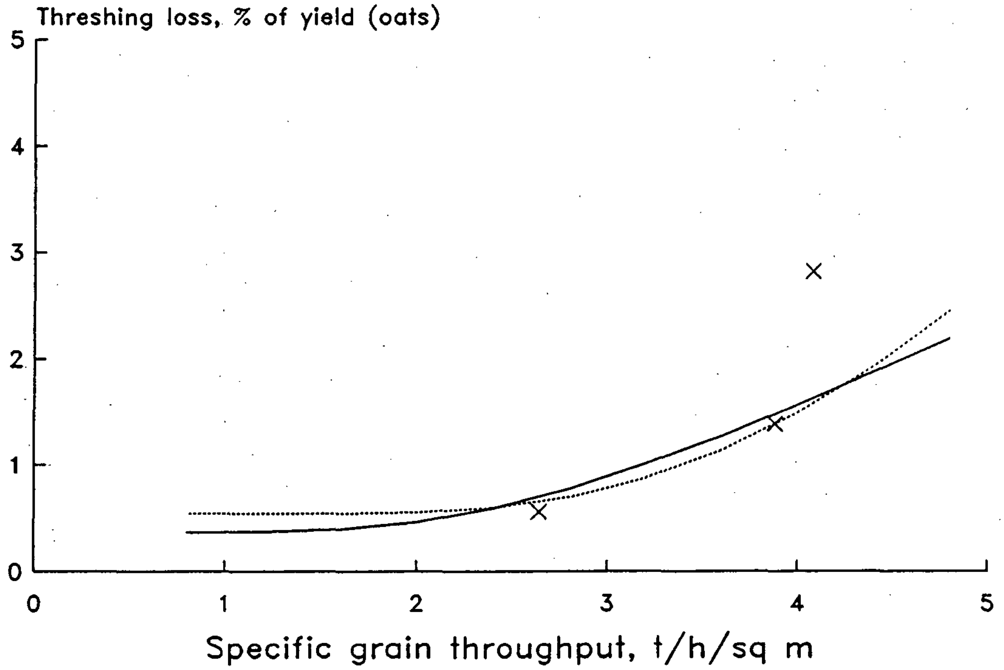


Fig. 4c Threshing loss as a function of specific grain throughput with a stripper header - oats (—— fitted direct, ... fitted from cutterbar equation)

Empirical studies have shown that a combine fitted with a stripper header produces a pattern of threshing losses distinct from those of the cutterbar machines. This is no doubt a consequence of (1) the substantial differences in the type of material other than grain (MOG) which, for the stripper, is mainly the flag leaf with a small proportion of straw, and (2) the different ratios of the MOG to grain of the two headers. For this reason, separate curves were fitted to the two distinct header types.

It is important to point out that in as far as it relates to workrate, the throughput of straw within a combine fitted with a stripping header is much lower than the throughput of straw when a cutterbar is used. This is a consequence of the stripper header harvesting only a small quantity of straw for any given level of grain throughput. Therefore any level of throughput of straw sustained by the stripper header corresponds to a much larger work rate than the cutterbar combine, since the implied throughput of grain is so much higher. Typically this is of the order of four to one. For example if both types of machines harvest one tonne of MOG, then the stripper is harvesting four tonnes of grain whilst the cutterbar machine is harvesting just one.

An alternative approach to calculating threshing losses in the combine was adopted to deal with the cutterbar and stripping header comparison. This is based on the premise that the same threshing loss equation can be used for both headers, but with an extra parameter to indicate the effect of the lower portion straw left by the stripper header. The MOG is considered in two fractions i) the material harvested by the stripper, which is mainly flag leaf, and ii) the straw fraction left behind. Both of these are harvested by the cutterbar. This method could equally well be used to assess the effect due to the height at which the cutter-bar operates. Formally the approach worked as follows:

Originally we had, for the cutter-bar header, the fitted equation:

$$L_T = a + b\,\exp(-c/s_t) \qquad \ldots (1)$$

where $s_t = A + B$, where A is the lower portion of straw and B is the stripper portion of straw.

Let us introduce p to measure the effect of the lower and stripper portions on the threshing loss and redefine $s_t = (1 - p)\,A + pB$. ... (2)

We want an equation of the form:

$$L_T = a + b\,\exp\,(-c'/((1-p)A+pB))$$

so that

$$c' = \frac{c((1-p)A + pB)}{A + B}$$

For the experimental data available generally 3B = A, so

$$c' = \left(\frac{3 - 2p}{4}\right) c$$

So the new threshing loss equation becomes:

$$L_T = a + b \exp(-c(3-2p)/4((1-p)A+pB)) \qquad \ldots (3)$$

where p is to be estimated for each crop from the stripper threshing loss data. For the stripper $A = 0$, $B = s_t$, for the cutterbar $A = 0.75s_t$, $B = 0.25s_t$ (typically).

Setting $q=4p/(3-2p)$, the simplified equation for stripper threshing losses is

$$L_T = a + b \exp(-c/qB)$$

Thus q=1 would correspond to the situation where threshing losses are purely a function of straw throughput and q=4 would correspond to the situation where threshing losses were purely determined by the stripper intake portion of the straw. Using the stripper header threshing loss data, the values obtained for q are:

	a	b	c	q
Barley	0.6907	55.42	7.92	2.37
Wheat	0.3153	96.78	11.57	3.20
Oats	0.54	62.27	11.26	2.69

These curves are plotted as dotted lines on Figs. 4a-c.

The differing values of q reflect the differing impact of the stripper portion of straw on the threshing loss. From these values it is apparent that in the case of wheat, q is closer to 4 which indicates that the stripper portion and not the residue portion of straw has most effect on the level of loss that is experienced. This explains why the increase in grain throughput capacity is less than that achieved in barley crops because the straw that is harvested by the stripper, though of small quantity provides a difficult separating task for the machine. This may be a result of the flag leaf wrapping around the grains and preventing separation. For barley however, the lower value of q suggests that the stripper portion of the straw has a lesser effect on threshing loss than in wheat and so a greater increase in throughput is achieved. Although this alternative approach looks plausible, it was not actually used and ultimately the fitted curve approach was used in the results presented.

4.3.3 Machine costs

Cost for capital goods$^{(22)}$ can be split into two parts: fixed unavoidable costs that accrue from ownership, and variable operating costs. The former is dependent upon expected rates of interest, inflation and depreciation. The latter varies according to how intensively that item of equipment is used and variables such as labour, fuel and repairs affect it.

4.3.3.1 Capital Costs

Combine capital cost is a function of the size of the straw walker area or the equivalent parameter in rotary separating systems. The standard width of cutterbar supplied with a combine may be assumed as a function of the straw walker area. The cost of a different size of cutterbar is proportional to the difference in width. The following were fitted to combine cost data (October 1988).

Capital Cost: $C_c = -9281 + 11920\ S$ straw walker
$C_c = 134087\ r$ axial flow

Standard Cutterbar Width: $W_p = 1.10 + 0.57\ S$ straw walker
$W_p = -2.39 + 11.71\ r$ axial flow

Cutterbar Cost:

The above cost is assumed to include the standard size of cutterbar. The farmer has the option of only having the stripper header or having both the cutterbar and stripper header available. The following, when summed with C_c, provides the necessary adjustment to the total capital cost that embraces the actual size of the header and its type.

Cutterbar only: $C_h = (W_A - W_P)\ 1730$
Stripper only: $C_h = W_S\ 2786 - W_P\ 1730$

Both headers: $C_h = W_S\ 2786 + (W_A - W_P)\ 1730$

The total capital cost of the combine is then

$$C_\Sigma = C_c + C_h$$

Capital costs are converted to annual costs using a discount factor p_d which is a function of the inflation and interest rates and the replacement interval of the combine(8).

4.3.3.2 **Repair costs**

Repair costs are a function of hours of use and can be estimated by the proportion $0.005 + 0.0002\ H$ of the capital cost of the machine(12).

4.3.3.3 **Fuel costs**

Fuel costs are a function of engine and combine size and are virtually independent of combine throughput. They are given by(12) $F = (4.5 + 2.0\ s)\ f_c$

4.3.3.4 **Realized rate of work:**

The spot workrate of a combine in hectares per hour (w) is given by

$$w_i = \frac{t_g}{y_i}$$

The overall workrate of the combine allowing a field efficiency factor, is $f_e\ w_i$

4.3.3.5 Annual combine costs

From the above equation, the fixed cost of combining is

$$C_F = C_\Sigma (p_d + 0.005)$$

and the variable cost of combining is

$$C_V = \sum_i (H_{Li} (W + 1.25 F) + H_{Ni} (W + F)) + 0.0002 H$$

Where $H_{Li} = H_i \, p_{Li}$ hours spent harvesting ith laid crop

and $H_{Ni} = H - H_{Li}$ hours spent harvesting ith normal crop

4.3.4 Workability

The workability criterion is defined by Audsley(12). Simply stated, the model is as follows. In any given day the rain is such that it is either possible to harvest or it is not. If a sufficient quantity fell on the previous day and/or today then harvesting is suspended until the model predicts that operations can resume. For example:

If k is the day, h_k the hours available for harvesting and R_k the rainfall. The cumulative rainfall on day k is defined thus:

$$Z_k = R_k \qquad k=1$$
$$Z_k = 0.2Z_{k-1} + R_k \quad k>1$$

This is saying that 20% of the rain falling on the previous day remains on the following day. Note also that rainfall over earlier days can also contribute to the work decision since we are dealing with a cumulative figure.
It is assumed that once a significant amount of rain falls (0.127cms) no combine-harvesting can take place. Furthermore, as the season progresses the number of potential workable hours declines from nine hours, at the start of the season, at a rate of 0.02h/day. Thus after seventy days 7.6 hours of work are available on a good day. This is described below.

$$h_k \left| \begin{array}{ll} = 9 - 0.02k & \text{if } Z_k < 0.127 \\ = 0 & \text{otherwise} \end{array} \right.$$

An analysis of how accurately this model calculates the workable hours was conducted and it was found to agree quite closely with meteorological records.

4.3.5 Drying costs

Daily moisture content (wet basis) of the grain in the field is a decreasing function of days. van Elderen(23,24) showed that following rainfall, the crop dried rapidly to its pre-rainfall level. Rainfall is therefore assumed not to affect the harvested moisture content of the crop. If there is sufficient rainfall to suspend harvesting then when harvesting is resumed (perhaps the next day) the crop has had sufficient time to dry back to its pre-rainfall level.

After harvesting, the grain is placed in a wet grain store, in which safe storage time is a function of grain moisture content. It is then dried as soon as possible in a high temperature grain drier, to its final storage moisture content. In the model these act as constraints on the harvesting system which must stop if the grain cannot be dried. In this analysis a large drier was specified so as not to impose a constraint on either cutterbar or stripper system.

Annual fixed cost of drier

$$D_F = D_C \cdot p_d$$

Variable cost of drier

$$D_V = f_d \cdot H_d$$

Fixed cost of wet grain store

$$B_F = B_u \cdot B_A \cdot p_d$$

4.3.6 Total cost

Total annual cost of harvesting (with one combine)

$$T = D_F + D_V + B_F + C_F + C_V + G_L + L_{H\Sigma} + L_{T\Sigma} + L_{S\Sigma}$$

$$\text{where } G_L = \sum_{i=1}^{n} (a_i - \sum_{k=1}^{T_d} a_{ik})\, y_i\, V_i$$

$$L_{H\Sigma} = \sum_{i=1}^{n} \sum_{k=1}^{T_d} L_{Hik}\, a_{ik}\, y_i\, V_i$$

$$L_{T\Sigma} = \sum_{i=1}^{n} L_{Ti}\, Z_i\, y_i\, V_i$$

$$L_{S\Sigma} = \sum_{i=1}^{n} \sum_{k=1}^{T_d} L_{Sik}\, a_{ik}\, y_i\, V_i$$

The area harvested on day k is limited by the area remaining and the available capacity of the combine, wet grain store and drier.

The harvest is simulated over ten years using weather data from the region of interest and the average annual cost over the ten years is calculated.

4.4 Results

In order that comparisons could be made between the two types of header, a series of hypothetical farms with differing crop patterns in different regions were harvested by a straw walker combine, and the size and throughput adjusted in steps of 0.5m^2 of straw walker area and 2t/h grain throughput respectively, until the optimum was reached. This was repeated for different sizes of farm.

In order to highlight any differences, extreme types of farm were selected ie moderate and high yielding and large and small areas for one combine. The average yield in England and Wales estimated by MAFF in 1988/89 was 6.39t/ha for wheat and 4.75t/ha for barley (5.35t/ha winter, 3.85t/ha spring). The effect on any particular farm can be inferred by interpolating between these results. Where there is no difference between the extremes of a parameter, it can be inferred that this parameter has no effect on the comparison.

Having determined the optimum size with a cutterbar header, in each case the relative benefit of a further purchase of a stripper header is examined. (Henceforth this is referred to as the accessory stripper system).

The relative benefit of possessing a stripper header instead of a cutter-bar was also examined and the optimum size of combine for use with a stripper header was determined. In this case it must be stressed that the model can only test for crops for which data on the stripper header is available.

The results are first calculated on the assumption that the time saved by finishing earlier with the stripper header is equal to the extra time needed to dispose of the standing straw (the 'no labour saved' option). The final section examines the benefit if no extra time is needed for this operation and therefore there is extra time available for autumn cultivations etc (the 'no labour extra' option).

The input parameters were selected to highlight pertinent features of the two methods. How well each system copes with each farm is reflected in the ten yearly average of harvesting costs.

Crop details:

Barley	Yield	moderate: 5 t/ha	very high: 9 t/ha
	laid or necked 40%		
Wheat	Yield	moderate: 6 t/ha	very high: 10 t/ha
	laid 3%		
Grain moisture content	Start	low: 18%	high: 22%
	Final 14%		
Wheat ripeness	20 days after the barley		

Farm details

Farm	Barley Area, ha	Barley Yield, t/ha	Wheat Area, ha	Wheat Yield, t/ha	Starting Moisture Content, %
1	200	5	200	6	18
2	100	5	100	6	18
3	100	9	100	10	18
4	-	-	200	6	22
5	-	-	200	10	22
6	-	-	400	6	22

4.4.1 Analysis of results:

The following assumes that the farmer starts with a given area of land and then wants to examine the likely changes in cost for each harvesting system, and the costs if he adjusts that land area up or down. "Optimum cost" means the minimum cost of the system with respect to the size of the combine straw walker area and the grain/straw throughput. These are adjusted until the lowest cost system is reached. In each case the stripper header cost is calculated firstly on the assumption that the farmer is also buying a new size of combine and secondly on the assumption he is retaining the existing size of combine.

It is essential to point out that the optimum cost in all these examples is calculated without regard to the full farming system cost. For example, there are post harvest activities which need to be carried out, for example burning the straw, and if these are started later they may constitute a much higher cost to the farmer than if they are started early. If for example a harvest finishes late, then some activities will be postponed while the harvest is still in progress. This postponement has its own inherent cost and this needs to be calculated, using an integer or mixed integer programming approach.

See tables 1-6 for the results for farms 1 to 6 respectively.

4.4.2 Farm 1

This scenario depicts a large moderate yielding farm with 400 ha of cereals split into equal areas of barley and wheat. The optimum cost per hectare for the cutterbar combine with a 5m header over a ten yearly period, is £88.3/ha. This occurs with a 6m^2 straw walker area combine working at a grain throughput of 14t/h.

The 3m cutterbar header costs less, as it does in all cases as there is no penalty within the simulation for high forward speeds with a cutterbar header. There is only a small benefit due to the header being cheaper. The required forward speed in most cases is excessive.

With a 5m stripper header as the only header, it is optimal to use a combine with 6.5m^2 of straw walker area at a rate of 24t/h. The average cost is £86.5/ha. However, with a 3m wide stripper header a smaller 5m^2 combine working at 18t/h is best, giving a lower average cost of £77.9/ha. A major cause of this effect is the forward speed of the combine which, with the stripper header, should be as fast as possible - in this case over 8 km/h is optimal and well within the capability of a stripper header. The 3m header also has lower fixed costs.

If the stripper header is purchased as an accessory for the existing 6m^2 combine, so that the size of the combine is fixed, the optimum cost is £90.1/ha with a 5m wide stripper at a throughput of 20t/h and £80.9/ha with a 3m stripper at a throughput of 18t/h.

Clearly on this farm a 3m wide stripper header saves both money and time. A 5m wide stripper header costs about the same as a cutterbar but saves time.

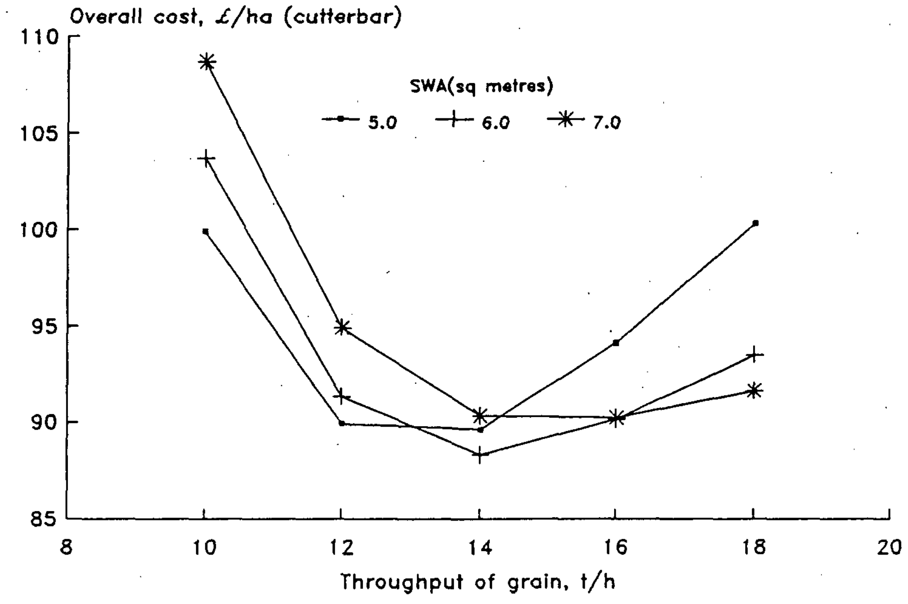
Table 1 also shows the cost for 25% more or less land and the cost on 25% more land <u>with the same harvesters</u>. The advantage of the stripper header is reduced on a smaller area. Its cost increases by £8/ha compared to £5/ha for the cutterbar header. The optimum combine size is much smaller. Equally the advantage of the stripper increases slightly with the larger area. With an increased crop area and the same sizes of combine, the stripper costs reduce by £5/ha compared to only £3/ha with the cutterbar header.

Table 1 Combine Costs

Farm 1 : Moderate yielding barley/wheat, low starting moisture content, no labour saved

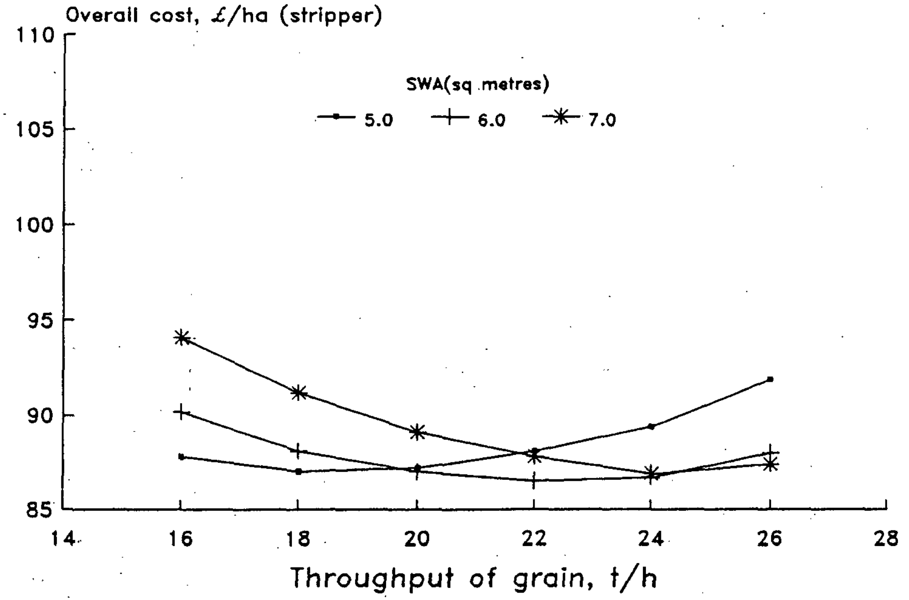
			LAND AREA (Hectares)											
			150, 150			200, 200			250, 250			300, 300		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	4.0	10	93.4	6.0	14	88.3	6.0+	16	85.2	7.0	16	84.4
		3	4.0	10	91.2	6.0	14	86.7	6.0+	16	83.8	7.0	16	83.2
	Stripper header only	5	4.0	14	96.0	6.5	24	86.5	6.5+	24	79.8	6.0	22	80.4
		3	4.0	14	85.7	5.0	18	77.9	5.0+	18	73.4	5.5	18	73.3
	Stripper accessory	5	4.0+	14	100.2	6.0+	20	90.1	6.0+	22	82.9	7.0+	24	82.4
		3	4.0+	14	88.2	6.0+	18	80.9	6.0+	18	75.3	7.0+	20	76.8

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha



SWA=straw walker area

Fig. 5a Average total annual harvesting costs by size of combine and forward speed with a cutterbar header



SWA=straw walker area

Fig. 5b Average total annual harvesting costs by size of combine and forward speed with a 5m stripper header

4.4.3 Farm 2

This scenario is the same as Farm 1 but on half the land area. In most cases the stripper header is not now more profitable than the cutterbar header. An interesting difference is that whereas on the large farm the 5m wide stripper should have a larger combine than the 3m stripper, this effect is reversed and the 3m stripper should have the larger combine. The explanation for this effect is as follows. In order to optimise the cost, the simulation has the option of reducing header loss, threshing loss or machine costs. Increasing speed will reduce header losses but will increase threshing losses by even more. Increasing the size of combine will allow the speed to be increased without increasing threshing losses but the reduction in header losses is less than the increase in machine costs per hectare on this smaller farm. Thus on a smaller farm a smaller combine is optimum. On the large farm, which is twice the size, the increased machine costs per hectare are halved and less than the consequent reduction in header losses and thus a larger combine is optimum. Otherwise the effects are the same as on the previous farm, that the stripper's advantage becomes less as the farm size becomes less and increases as the farm gets larger.

4.4.4 Farm 3

This scenario is comparable to Farms 1 and 2 but at almost double the yield. The results with the 5m stripper indicate the effect of being unable to achieve a sufficiently high forward speed to maintain low header losses as in a heavy crop it leads to too high a throughput for the combine. The best option is to use a smaller combine at a similar speed to the cutterbar header but this still costs at least £10/ha more than the 3m stripper header, working at a faster forward speed.

The cost of a 3m stripper header is about the same as the 5m cutterbar header and it works at a slightly higher throughput. As before the stripper has more advantage as the area increases and vice-versa.

At 400 ha, the optimum 5m cutterbar header combine needs 9.0 m^2 of straw walker area, which is impossible, and a throughput of 22t/h, costing £139.0/ha, compared to 7.5m^2 at 26t/h with a 5m stripper header costing £137.9/ha or with a 3m stripper header £122.4/ha. In this situation of two combines with a cutterbar versus one combine with a stripper header, the stripper header is extremely economical.

Table 2 Combine Costs

Farm 2 : Moderate yielding barley/wheat, low starting moisture content, no labour saved

			LAND AREA (Hectares)											
			75, 75			100, 100			125, 125			125, 125		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	2.5	6	115.3	3.0	8	105.3	3.0+	8	98.4	3.5	8	97.7
		3	2.5	6	111.1	3.0	8	102.2	3.0+	8	95.7	3.5	8	95.1
	Stripper header only	5	2.0	8	124.2	3.0	10	111.1	3.0+	10	102.7	3.5	12	102.3
		3	2.0	8	113.7	3.5	14	101.0	3.5+	14	91.9	4.0	14	91.8
	Stripper accessory	5	2.5+	8	133.0	3.0+	10	117.3	3.0+	10	107.7	3.5+	12	107.3
		3	2.5+	10	118.8	3.0+	12	104.5	3.0+	12	95.9	3.5+	14	94.9

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

Table 3 Combine Costs

Farm 3 : High yielding barley/wheat, low starting moisture content, no labour saved

			LAND AREA (Hectares)											
			75, 75			100, 100			125, 125			125, 125		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	3.5	8	168.1	5.0	12	156.1	5.0+	14	151.8	6.0	14	149.0
		3	3.5	8	163.6	5.0	12	152.9	5.0+	14	146.4	6.0	14	146.4
	Stripper header only	5	3.0	10	180.2	3.5	12	165.9	3.5+	14	159.7	4.5	16	156.1
		3	3.0	10	168.4	4.0	14	154.0	4.0	16	145.9	5.0	18	143.7
	Stripper accessory	5	3.5+	12	190.3	5.0+	16	174.7	5.0+	16	161.2	6.0+	20	163.1
		3	3.5+	12	174.4	5.0+	16	159.3	5.0+	18	146.7	6.0+	20	147.3

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

4.4.5 Farms 4-6

Stripper header losses in barley are generally less than with a cutterbar header. However in wheat, header losses are generally slightly higher, particularly at low forward speeds. As with barley, the stripper does better in laid crops. Farms 4-6 look at the stripper on a farm with only wheat, mostly standing, which is the worst case for comparison to be made. They also look at the effect of starting at a higher moisture content. On 200 ha of moderate yielding wheat (Farm 4) with a 5m cutterbar header, the optimum is a $3m^2$ combine at 8t/h grain throughput costing £104.9/ha. The best stripper system is a 3m header, $3.5m^2$ combine, 14t/h grain throughput costing £112.8/ha. All these combines are smaller than any currently on the market.

With high yielding wheat (Farm 5), the cutterbar optimum is £151.8/ha ($4.5m^2$ at 12t/h) compared to £170.3/ha with a 3m stripper header ($4.0m^2$ at 14t/h).

With a larger farm size (Farm 6), the same effect on combine size with the stripper is seen as with the barley/wheat farms. On smaller areas the optimum compared with the cutterbar is a larger combine with the 3m header and not with the 5m header. At large areas, the optimum is a smaller combine with the 3m header and a larger combine with the 5m header. The 5m cutterbar header optimum is £88.3/ha ($5.5m^2$ at 14t/h) compared with £88.7/ha for the 3m stripper header ($5.0m^2$ at 18t/h). It is perhaps worth noting that the forward speed is 10 km/h.

The effect of the higher starting moisture content is to reduce the overall cost by £3-4/ha, but it has little effect on the optimum size. The only change to Farm 4 is to reduce the optimum throughput of the 5m stripper from 12t/h to 10t/h (cost from £127.1/ha to £123.9/ha).

Table 4 Combine Costs

Farm 4 : Moderate yielding wheat, high starting moisture content, no labour saved

			LAND AREA (Hectares)											
			150			200			250			250		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	2.5	6	115.8	3.0	8	104.9	3.0+	8	102.4	4.0	10	98.7
		3	2.5	6	111.5	3.0	8	101.7	3.0+	8	99.6	4.0	10	96.1
	Stripper default	5	2.5	10	137.2	3.0	10	123.9	3.0+	12	115.7	4.0	14	115.0
		3	2.5	10	125.9	3.5	14	112.8	3.5+	14	104.2	4.0	16	103.4
	Stripper accessory	5	2.5+	10	145.6	3.0+	10	130.2	3.0+	12	120.7	4.0+	14	120.0
		3	2.5+	10	130.9	3.0+	12	116.8	3.0+	12	110.6	4.0+	16	106.4

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

Table 5 Combine Costs

Farm 5 : High yielding wheat, high starting moisture content, no labour saved

			LAND AREA (Hectares)											
			150			200			250			250		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	4.0	10	163.5	4.5	12	151.8	4.5+	14	151.9	6.0	16	145.9
		3	4.0	10	159.2	4.5	12	148.5	4.5+	14	149.2	6.0	16	143.3
	Stripper default	5	3.0	10	197.3	4.0	16	182.5	4.0+	16	175.1	5.0	18	172.9
		3	3.0	10	185.3	4.0	14	170.3	4.0+	16	162.8	5.0	18	159.8
	Stripper accessory	5	4.0+	12	209.1	4.5+	14	189.7	4.5+	16	178.2	6.0+	20	179.4
		3	4.0+	14	192.5	4.5+	16	174.6	4.5+	16	163.9	6.0+	20	163.4

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

Table 6 Combine Costs

Farm 6 : Moderate yielding wheat, high starting moisture content, no labour saved

			LAND AREA (Hectares)											
			300			400			500			600		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	4.5	12	94.4	5.5	14	88.3	5.5+	18	90.0	7.0	18	85.1
		3	4.5	12	92.3	5.5	14	86.6	5.5+	18	88.6	7.0	18	83.8
	Stripper default	5	5.0	18	108.4	6.0	22	98.7	6.0+	24	92.9	7.0	24	92.3
		3	5.0	18	96.8	5.0	18	88.7	5.0+	18	84.7	5.5	18	84.6
	Stripper accessory	5	4.5+	16	112.6	5.5+	20	102.2	5.5+	22	96.3	7.0+	24	94.8
		3	4.5+	18	99.5	5.5+	18	90.8	5.5+	18	86.1	7.0+	22	87.5

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

4.4.6 Value of finishing earlier

Section 3 quantified the savings in pounds per hour, of finishing the harvest earlier. The saving has been calculated at £60/h. This has been used to determine the savings per hectare of Farm 1, and the cost per hectare has been adjusted accordingly. If, for example, there are no additional post harvest activities caused by using a stripper header, e.g. the straw is burnt in both cases, the following adjustments to farm cost per hectare can be made (see Table 7). Clearly if no extra labour is required post-harvest, the stripper system is very cost effective on this farm.

The same calculation applied to the six other farms to compare the 5m wide cutterbar with the 3m stripper header as an accessory, shows the costs for the extremes of no saving in labour, i.e. the time saved by the stripper is used to deal with the straw, and the situation when time is saved due to the stripper header, Table 8.

Table 8: Total cost of harvesting with 5m cutterbar and 3m stripper header, including value of finishing harvest early, £/ha

		3m Stripper header accessory	
Farm	5m Cutterbar	No labour saved	No labour extra
1	88.3	80.9	73.6
2	105.3	104.5	85.0
3	156.1	159.3	142.5
4	104.9	116.8	95.5
5	151.8	174.6	156.9
6	88.3	90.8	82.7

The savings on the wheat/barley farms now become substantial, reach £15-20/ha. The only farm on which the stripper is not more profitable is the high yielding all wheat farm on which the cost if no extra labour is needed to dispose of the straw is similar to the cutterbar cost.

4.4.7 Discussion of results

It is evident that the optimum throughputs with the stripper header systems are larger than with the cutterbar header systems. While the optimum straw walker area is often less, it is sometimes more with the 5m stripper header where it is more important to obtain the benefit of reduced header losses from higher forward speeds. Overall the results suggest that low yielding large barley farms are ideal for the stripper. Conversely the stripper is revealed as not economical on high yielding all wheat farms. There are three factors in the data which combine to cause this:

1. The flag leaf which is present in both the cutterbar and stripper MOG appears to be the factor which ultimately limits the throughput and thus the workrate, the other portion having a much lower effect. This is indicated by the q-factor in section 3.2.3 which for wheat is close to 4.0 indicating the reduced advantage to the stripper system in wheat versus barley.

2. Header losses reduce with speed with the stripper. It is best to operate at 7 km/h or more.

3. The stripper is better than a conventional header in laid or badly necked crops and it was assumed that a large proportion of the barley was badly necked but very little of the wheat was laid.

There is relatively little stripper header data available compared to the amount available for the cutterbar system and though the present data indicates these effects, further measurements on some specific aspects would be helpful. A second year's experiments with a Claas Cylinder Separation system combine suggests less effect of the flag-leaf on threshing losses, but these are not comparable with the earlier straw walker combine experiments. It is impossible to know whether this was a year effect or a combine separation system effect and so this data was not used. Subsequent farmer operation of rotary combines with stripping headers also suggests that much higher outputs can be achieved.

Threshing losses with a cutterbar header are fitted to many years' data whereas the stripper data is only fitted to one. It is evident that the threshing losses with the cutterbar which were measured at the same time as the stripper data, are higher than normal for wheat and lower than normal for barley. It is reasonable to argue that these losses are a better basis on which to compare the stripper and cutterbar headers, even though the results would not be a good estimate of the long-term performance of the cutterbar. The corresponding long-term data for the stripper does not yet exist.

The method adopted was to take the standard threshing loss as fitted to all the cutterbar data and modify it for the measured performance of the two headers:

$$L_T = a + b \exp(-c/qs_t)$$

This factor q has already been calculated for the stripper header threshing losses in Section 4.3.2.3. Given the corresponding threshing losses measured with the cutterbar in the same conditions, the values of q which fits these losses are:

	Cutterbar	Stripper
Barley	0.90	2.37
Wheat	1.32	3.20

The optimum size and throughput with a 5m header with no labour saved was then recalculated for the six cases (the costs from the losses fitted to all the data are given in brackets).

	Cutterbar			Stripper		
Farm	SWA	TRPUT	COST	SWA	TRPUT	COST
1	6.0	14	91.6 (88.3)	6.5	22	88.1 (86.5)
2	3.5	8	108.8 (105.3)	3.0	10	112.2 (111.1)
3	5.5	12	161.7 (156.1)	4.0	12	167.8 (165.9)
4	4.0	8	115.9 (104.9)	3.0	10	124.9 (123.9)
5	6.0	12	168.7 (151.8)	4.5	14	183.8 (182.5)
6.	7.0	14	98.4 (88.3)	6.5	22	100.2 (98.7)

Table 7 Adjusted Combine Costs

Farm 1 : Moderate yielding barley/wheat, low starting moisture content, no labour extra

			LAND AREA (Hectares)											
			150, 150			200, 200			250, 250			300, 300		
Separator	Header	Header size, m	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST	SWA	TRPUT	COST
Straw Walker	Cutter-bar	5	4.0	10	93.4	6.0	14	88.3	6.0+	16	85.2	7.0	16	84.5
		3	4.0	10	91.2	6.0	14	86.7	6.0+	16	83.8	7.0	16	83.2
	Stripper default	5	4.0	14	82.6	6.5	24	74.4	6.5+	24	70.1	6.0	22	72.5
		3	4.0	14	72.2	5.0	18	70.6	5.0+	18	70.3	5.5	18	70.2
	Stripper accessory	5	4.0+	14	86.7	6.0+	20	80.1	6.0+	22	75.0	7.0+	24	72.7
		3	4.0+	14	74.7	6.0+	18	73.6	6.0+	18	72.2	7.0+	20	71.0

SWA = Straw walker area (m^2)
TRPUT = Throughput of grain (t/h)
\+ = Fixed at this size, optimised throughput only
COST = Total cost, £/ha

There is little overall effect on the three barley/wheat farms (Farms 1-3). The value of the stripper compared to the cutterbar is only increased by £2-3/ha. However on the all wheat farms the size of combine needed with a cutterbar header is increased by a third, giving an overall cost increase of about 10%. The costs of the two headers are now comparable on Farm 6 (large, low yield wheat) even if no labour is saved. The extra cost of the stripper header compared to the cutterbar header has been reduced to £10-15/ha on Farms 4 and 5. This means that in the 'no labour extra' case, the stripper header is better than the cutterbar header in all cases. Although the economics of the stripper have been improved, the change is insufficient to alter the general conclusions that low yielding badly necked barley is ideal for the stripper economics and high yielding standing wheat is marginal.

4.5 Conclusions

On farms with an equal area of wheat and barley, the distribution most usually found in the UK, the stripper header was better than the cutterbar header. On large moderate yielding farms where the system includes barley, there are clear unquestionable advantages in the stripper system. Although the results are less clear on high yielding wheat farms, the faster workrate can result in a more favourable cost profile if the farmer takes full advantage of finishing earlier by burning or incorporating the straw, providing this takes no extra labour.

Threshing and header losses are an important component of the cost comparison between stripping and cutterbar headers. Conventionally one would expect a direct relationship between separating loss and straw throughput. The relatively little experimental evidence with the stripper suggests this is not strictly true, especially in wheat. Although the capacity of a combine and stripper header is higher in wheat crops, this is not proportional to the reduction in straw throughput. This information has consequences for conventional advice on the height of the cut with a cutterbar. Further experiments are needed to clarify this.

Forward speed has an effect on header losses with the stripper header. Speeds in excess of 7 km/h should be used to keep these at a low level. Header losses in standing versus laid crops also need further study with both types of header.

5. The economics of whole crop cereals harvesting

5.1 Introduction

The combine harvester is a very large sophisticated and expensive machine. It produces a good sample of grain for sale, which being dense is easy to transport from the field. The combine is therefore ideal for large cereal farms which have no use for the straw, which can either be burned or chopped and incorporated.

The livestock farmer who wishes to harvest the straw, needs to enter the field with another machine. This has to pick up the straw from the ground where the combine has left it, with associated losses, particularly of fine fractions. There are also potential drying problems where the straw is close to the ground. The straw, even with the densest baler is not very dense and transport is time consuming for the quantity and value moved. For this reason there are many attempts to improve the packaging, such as very dense briquettes, to produce an easier to handle product. Many farmers merely stack rows of bales along the headland, preferring to move them when more time is available in the winter.

An alternative proposition is to remove the need for two field operations by harvesting the whole crop, both grain and straw, at one go. This can be achieved using a forage harvester which the livestock farmer almost certainly has anyway for silage making. Although slower for grain harvesting, it will be faster than baling and so taken together could be advantageous. The grain/straw mixture is loaded into trailers and taken to the farmstead. At this point there are several different courses that can be taken with the grain/straw mixture:

Proposal A: Separate the grain and straw at the farmstead, sell the grain in the conventional manner and use the straw on the farm.

Proposal B: Preserve the grain/straw using urea and then feed it to the livestock.

Proposal C: Preserve the grain/straw mixture using urea, and at a later date separate the mixture into urea treated grain, which is still suitable for industrial purposes, and urea treated straw which can either also be used for industrial purposes, or more likely fed to livestock.

This report analyses these options in more detail and examines the effect on farm profits of introducing these systems.

5.2 The systems

5.2.1 The farms

One of the main features of these alternatives is their use of a forage harvester, rather than a combine harvester. An initial question is therefore whether this system would be cheaper than a combine harvester system on an all-cereal farm. Clearly a market would need to be found for the straw in this case. The system is likely to be more attractive to mixed cereal-livestock farms already using a forage harvester for silage making. This could be particularly true for smaller farms or farms with a relatively small cereal area.

A particular size of farm with a specific labour force can show benefits to one system just because the ideal labour force for that system more closely matches the labour force available. To average out these incremental effects caused by discrete units, all calculations will be carried out on a per hectare basis, with the machinery sizes aimed at the relevant size of farm. In practice any saving will be gradually achieved due to changes in crop area, machinery or men over many years.

The following farms will be considered:

Farm 1: Combinable crops farm, typically 250 ha. Combine size 11 t/h overall workrate, tractor size 60 kW. These sizes have been found to be optimal (Section 4.3).

Farm 2: 50% grass, 50% cereal farm, typically 200 ha. Combine size 9 t/h overall workrate, tractor size 60 kW. 2/3rd grass area for first cut silage, 1/3rd grass area for second and third cuts. Only 70% of labour hours available for cereal work due to livestock commitments.

The effects on farm profits, cropping, labour and machinery are calculated using the Arable Farm Model(5). This is a linear programming model which finds the strategy which maximises long-run farm profits.

Full details of the farms are given in Appendix 1. Briefly the cereal farm grows winter wheat, winter barley, oilseed rape and spring beans. A typical size of 250 ha is considered representative of a sizeable combinable crops farm. Unlike most combinable crops farms however, it is assumed the straw is baled and sold in order to provide a fair comparison with whole crop harvesting. The combine harvester is assumed to be replaced by a forage harvester and a contractor is used to harvest the rape and beans.

The cereal-livestock farm is 200 ha equally divided between a 3 year grass ley and cereals (winter wheat, winter barley and spring barley). The straw is baled. Proposal A reduces the straw available for bedding but is otherwise identical to the combine system as the grain can be sold or used. Proposal B requires all the grain and straw to be fed and thus will probably require more livestock even if previously all the grain and straw was used on the farm. Proposal C again replaces straw for bedding with, possibly, straw for feeding. Note that a combination of B and C could be considered where some whole crop is fed and some sold.

On the livestock farm, it is assumed that a proportion of the time each week will inevitably be devoted to livestock tasks, degrading the labour available for arable tasks. This degradation is taken to mean that only 70% of the total time available is usable on arable tasks.

5.2.2 The fate of the straw

What use is made of the straw from these farms with the combine harvester and baler? The cereal farm is assumed to sell the straw.

Nationally over 70% of wheat straw and over 30% of barley straw(25) is used for bedding. Very little wheat straw is fed to livestock but over 50% of barley straw is fed. Feeding trials(26) have shown that the degradability and intake of winter barley straw is more comparable with winter wheat. Thus a better classification would be straw from winter cereals and straw from spring cereals. The latter is the straw that should be mainly fed.

Straw can also be treated on farm with ammonia to improve its feed value and spring barley straw can become as good a feed as hay. However, both the original straw and the effect of the treatment can be very variable in terms of feed value.

Many farms now use slurry systems for handling waste and hence have only a small requirement for bedding straw. On some farms this is reduced even further by the use of sawdust or sand. Thus some farms will have no demand for bedding straw.

A major problem with straw is transport costs. HGCA(27) found that grain transport costs were (2.85 + 0.03x) £/t for a distance of x miles. These are typically 25t lorries. Settled chopped straw typically has a density of 0.12 t/m^3 so that these lorries would only hold 4.2t giving a transport cost of (17.0 + 0.18x) £/t. Bales allow higher stacking and, although conventional bales are lower in density, 7t loads are possible. Loads of 11t are possible with Hesston bales.

5.2.2.1 Proposal A

The grain/straw mixture can be partly dried before separation with the option of using some of the straw as fuel, though care will be needed not to ignite the straw being dried. After separation the grain can be dried, again using straw as fuel. The straw can either be dried or, more likely, stored with a preservative such as urea. If stored with a preservative it is unsuitable for bedding. If bedding is required either some straw will need to be dried to a safe storage moisture content or the harvest will have to be delayed until the straw has dried.

The cereal farm sells the straw which if not dried, must therefore be stable in air while it is transported. Transport costs will be higher than for baled straw, £10/t at 50 miles. As the straw is chopped it will require different handling equipment which may be a disincentive to the livestock farms buying the straw.

The proposal will be evaluated on the assumption that the straw is treated with urea and sold/used at its feeding value, with a negligible increase in transport costs.

5.2.2.2 Proposal B

The grain/straw mixture is treated with urea and sold as a livestock feed so there is no opportunity to obtain bedding straw. Transporting the mixture on a 50 mile journey would cost £26/t. Sold separately as grain and baled straw (assuming conventional bales forming at 7t load), the corresponding costs would be £4.35/t grain and £15.54/t straw, or £10/t of grain and straw. There is thus an additional cost of £16/t which would reduce the price the farmer was offered. The inescapable conclusion therefore is that the silage must be used within a few miles of its production to be economical.

On the livestock-cereal farm transport is no longer a problem, however the farm is now required to keep sufficient livestock to consume the whole of the farm's production (or sell to a near neighbour), as by definition there is no combine harvester to harvest some grain for separate sale.

The proposal will be evaluated on the assumption of negligible increase in transport costs.

5.2.2.3 Proposal C

The grain/straw mixture is treated with urea and sold for industrial use. If all the mixture is sold, the same comments as above apply to transport reducing the value of the farm by £16/t for a 50 mile journey. The additional cost for a 10 mile journey is £12/t.

An alternative is to separate the grain and straw on the farm and only use the grain for industrial purposes. The change in transport costs would then be similar to proposal A, that is £10/t higher for the chopped straw if it was transported 50 miles from the cereal farm.

The proposal will be evaluated on the basis of on farm separation and negligible increase in transport costs.

5.2.2.4 Bulk density

A clear conclusion from all these proposals is the need to be able to package the chopped straw or whole crop silage at higher densities than 0.12 t/m^3 in order to eliminate the transport cost penalty. The density required to eliminate the penalty is 0.457 t/m^3. Assuming there is no advantage due to using air spaces within each other's bulk, this is equivalent to achieving a straw density of 0.200 t/m^3 which should be compared with a Hesston bale which only reaches 0.160 t/m^3, i.e. difficult.

However, initially, all the proposals will be evaluated on the assumption that the product can be sold or used at its value with no reduction for transport penalties. This implies that the farm growing only cereals is close to farms with livestock to consume his produce. This is not too unrealistic as otherwise there would have been little market for the baled straw.

5.2.3 Crop gross margins

The first step is to define how much grain and straw (a more accurate term is material other than grain) is present to start with in the field. It varies widely from year to year, field to field and variety to variety but a good central estimate is that there is the same amount of grain and straw, so this will be the initial assumption:

> The ratio of dry matter yield of grain at combine maturity to the dry matter yield of straw above 5 cm from the ground is 1.0. The moisture content of the grain at this point(28) is 30%. The moisture content of the straw at this point is 50%. The dry matter yield of wheat grain is 7 t/ha (8.2 t/ha at 15% mcwb). All yields of winter barley and spring barley are assumed to be 82% and 70% respectively of wheat. (All yields in the rest of this section refer to winter wheat and the yields of barley are calculated pro-rata). The average moisture content of the harvested grain is 19%.

5.2.3.1 Combine harvester

The front end loss (dry matter + shedding + header) is estimated(29) to average 7% over the harvest, compared to 4% if harvested at maturity. Adding a threshing loss of 1.5%, this gives a final harvested yield of 6.41 tDM/ha. This has to be dried, by an average of 5% from 19% to 14% in a high temperature grain drier.

Assuming a cutterbar height of 15 cm (a higher cut might be used on a cereal farm but the farmer wants the straw), 10% of the straw above 5 cm will remain uncut, giving a combine straw throughput of 6.3 tDM/ha. Loss of leaf and chaff means that 75% of this will be harvested in the bale giving a harvested straw yield of 4.73 tDM/ha.

The value of wheat grain is taken as £102/t. The value of straw estimated from its feed value(26) using the formula(3) 12.7 (ME) + 1.93 (CP%) - 63.4 £/tDM is £22.5/t. This is also similar to the ex-farm prices at which straw is commonly sold. The variable cost of drying the grain (fuel) is £2.02/t(6).

5.2.3.2 Proposal A

If germination is required then crops must be harvested after the moisture content has reached 30%(30) but otherwise germination is not noticeably affected by using a forage harvester. Grain/straw separation in a wind tunnel(30,31) was not entirely successful at removing all the straw with acceptable grain losses but it can be assumed that methods can be found to overcome these problems - for example a stationary version of a combine harvester.

Whole crop harvesting is known to lead to a greater proportion of damaged or broken grains. Boyd(30) found 20% damaged versus 4% from a combine, Wilton(31) found 3-6%. It is likely that the majority of damaged grain will be sellable but there will be some loss of weight as chips are sieved out of the grain. For this report a loss of 0.5% of the grain to the straw will be assumed.

Boyd(30) suggests that a cutterbar is needed to reduce front-end losses to an acceptable level. The front-end losses will thus be unchanged from the combine system unless the harvest is faster but it is likely that an on-farm system would have a similar workrate. Steps have to be taken to modify a conventional forage harvester to prevent a substantial loss of grain through joints, but provided this is done, losses should be small, say 0.5%. The harvested yield is thus 6.44 tDM/ha. This again is dried by 5% but in this case using straw. The drier is assumed substantially less efficient than an oil fired high temperature drier, at 10 MJ/kg H_2O. The moisture content of the straw will give a calorific value of 15 MJ/kg DM. Thus 0.32 tDM/ha of straw is needed to dry the grain. Allowing 1 MJ/kg H_2O for start-up and for electricity for fans, the drying variable cost is £0.40/t excluding the straw.

Even with whole-crop harvesting it is likely that some of the light fraction (chaff) will be lost. As a cutterbar is still used, the cut height will be unchanged. The net yield of straw will thus be 5.67 tDM/ha plus 0.03 tDM/ha of grain. As this is moist straw it will have to be preserved as a silage by adding urea.

To calculate the amount of urea needed systematically the following assumptions will be made:

(i) the grain and straw have the same drying rate constant and the same equilibrium moisture content of 15% from start points of 30% and 50% given above, i.e. $\dot{m}_G = -k(m_G-m_e)$, $\dot{m}_S = -k(m_S-m_e)$

(ii) the amount of urea added is calculated to give the same concentration in the moisture in the straw, based on 7% urea by weight added to 40% m.c. straw(32) which corresponds to 0.175t urea/t moisture.

Reference 28 shows that grain typically takes 10 days to drop from 30% to 20% m.c. As the average moisture content of the harvested grain is 19%, the calculated average moisture content of the harvested straw is 24%. The amount of urea needed is thus 4.2% by weight. Taking the urea price as £105/t, this costs £4.41/t straw.

Urea treatment affects both the metabolisability of the straw and the intake by cattle. The effect of ammonia on the straw is however notoriously variable. Applying the results of treatment with anhydrous ammonia(26,33) to straw and straw fractions show an increase in ME from 6.6 to 8.3 in winter cereals and 7.6 to 8.9 in spring barley giving a value of £40.6/t and £47.1/t respectively. This conforms to the average improvement in ME of 21% assumed by Doyle(34). 21% is considerably less than the improvement found by Orskov in one treatment applied to wheat, though more than the effect on barley. In addition the crude protein is increased by the added nitrogen as well as the degradability and hence intake of the straw.

The intake was shown(35) to be proportional to K/(1-a-0.75b) where a, b, c are the constants in the degradation equation a+b(1-exp(-ct)). Taking an average value of c for winter cereals of 0.0341, intake is then proportional to K/(1-D) where D is the 41h degradation expressed as a proportion. The 41h degradability was increased by treatment with urea(26) from 36.5% to 46% for winter cereals which implies an increase in intake of 18% of straw which is worth £19/tDM.

In theory this should be added to the value of the treated straw. However it seems more likely that this amount should be subtracted from the value of the untreated straw. The prediction of level of intake(3) using $(102q + 31.5)W^{0.75}/1000$ which was almost certainly mainly derived from hay and silage based rations, gives too high values for the untreated straw, particularly winter barley. The value of the untreated straw for feed is thus predicted as £4/t! It must be supposed that either the effect is little understood or that the market value of untreated wheat straw is supported by other uses such as bedding. It has already been stated that 70% of wheat straw is used for bedding. Of course it can also be treated with ammonia to raise its value. From the above analysis, a treatment cost of £18/t would raise its value to £40.6/t which would support the current straw price of £22/t.

There is a suggestion in the data that the intake of wheat straw is higher than that of barley straw for straw of equal value. As there is insufficient evidence however this effect is assumed not be exist.

On feeding out there will inevitably be some small loss of dry matter in ensilage which is taken to be 5%.

Note that unless some straw is sufficiently dry to store without urea, or is dried, the farmer will have no bedding straw.

5.2.3.3 Proposal B

Harvesting started when grain is at 35% m.c., will reduce front-end grain losses to 5%. Otherwise the grain harvested will suffer the same losses as above giving a yield of 6.58 tDM/ha. Assuming the same workrate as the combine, the average grain moisture content will be 23% and the average straw moisture content will be 35%. The straw yield will be 5.99 tDM/ha. Thus the combined yield will be 12.57 tDM/ha at a moisture content of 29% which will require 5% urea by weight. Assuming again a 5% loss of dry matter on feeding out, the amount fed to cattle will be 6.25 tDM/ha grain mixed with 5.69 tDM/ha of straw.

Assuming the urea has no effect on the feed value of the grain, but the same effect as above on the straw, gives a combined 12% increase in feed value for the silage which is in agreement with the in-vivo analysis(36) and a 6% increase in degradability, giving an overall 19% increase in effective ME due to increased intake. However in-vivo analysis and feeding trials(36) suggest this improvement is not achieved. In-vivo analysis (with soyabean meal) suggested the untreated silage was better and the treated silage worse than the in-vitro analysis indicated. This was also true of the caustic soda treated silage included in the experiment. This is in agreement with the performance generally found with caustic soda treated straw which generally gives high intake levels, but lower live weight gain than would be expected from the in-vitro analysis.

Intake with no concentrate was the same or lower than untreated whole crop silage, but with a rolled barley concentrate (which seems like coals to Newcastle), intake was increased by 13%. However even with the increased intake there was little evidence of increased live weight gain compared to the untreated whole crop silage. The increased intake and ME of straw found by Orskov(26) came with a sugar beet pulp based concentrate and it may be that this provides the rumen microbes with a better basis to degrade the straw than rolled barley and soyabean meal.

An alternative explanation is that the high level of degradable grain means that intake is no longer limited by the rate at which the fodder can be degraded and thus urea treatment gives no intake increase. Thus the whole crop silage is assumed to have an effective ME of 10.0 unmodified by any change in intake.

The value of a feed depends on the way it is used. Using the feed analysis described in Reference 3, the substitution value of whole crop silage in a range of fattening situations was:

Liveweight	Daily gain	Value
300 kg	1.0 kg	£81.2/t DM
300 kg	0.5 kg	£67.4/t DM
100 kg	0.75 kg	£80.3/t DM

Clearly this demonstrates that the feed must be used to obtain high levels of liveweight gain to obtain its full value. If it is then its value is £80.8/t DM.

5.2.3.4 Proposal C

This proceeds the same as the above except that instead of feeding the silage, it is separated and used for industrial purposes. Assume it is separated on the farm. The straw, now urea treated, is used as feed and the grain in sold as normal. Separation is assumed to occur at a time when labour is not required elsewhere, so that the marginal cost of labour is zero.

5.2.3.5 Summary of gross margins

	Conv.	A	B	C
Grain yield t DM/ha	6.41	6.44	6.25	6.25
Straw yield t DM/ha	4.73	5.39	5.69	5.69
Grain value, £/t @ 14% m.c.	102	102	80.8 (DM)	102
Straw value, £/t @ 15% m.c.	22.5	40.6		40.6
Variable cost, £/ha	216	216	216	216
Drying, £/ha	15	3	-	-
Twine, £/ha	1	-	-	-
Urea, £/ha	-	30	93	93
Gross margin, £/ha	653	772	656	704

5.2.3.6 Gross margin in model

The model automatically reduces the yield of cereals in unfavourable rotations or if planting is delayed and thus for any given set of data, the resulting yield cannot be predicted. The maximum yield for the conventional system was input as 8 t/ha and resulted in a net yield of 7.58t/ha or 6.52 tDM/ha. The input yields for the three proposals were thus input as modified versions of 8t/ha, namely 8.04, 7.80 and 7.80 respectively.

5.2.4 Harvest workrates

The logistics of the operation are analysed in this section using by the farm transport model(37). This takes account of loading/unloading, hitching/unhitching, travelling and waiting times to calculate an overall workrate for a system from a given machine workrate.All the systems are assumed to be operated by a three man team and are evaluated operating on a field whose distance from the farmstead is ½ km over road on which the travel speed is 20 km/h, 1 km over track at a travel speed of 15 km/h and 0.4 km to the centre of the field at a travel speed of 10 km/h. The forage harvester is a precision chop forage harvester costing £12,000.

5.2.4.1 Combine harvester system workrate

The system consists of two operations, firstly grain harvesting and secondly straw baling and carting. The combine harvester workrate in wheat is (0.1 x yield) h/ha. The grain is carted by two tractors with 8t grain trailers. The straw(3) is baled at the rate of 12 man mins/t and carted to the farmstead at the rate of 18 man mins/t giving an overall rate of 0.5 man h/t.

5.2.4.2 Proposal A workrate

A forage harvester in cereals was capable of a spot workrate of 1.05 ha/h with a tractor giving 49 kW at the pto(32). This corresponds to an overall workrate of 0.83 ha/h using the 60 kW tractors of the model and allowing for 70% field efficiency. The harvester pulls a trailer which when full is unhitched and replaced by an empty one. A transport tractor hitches on to this trailer and takes it to the farmstead to unload. Assuming the capacity of the trailers could be doubled by fitting high sides as for forage harvesting but sealed to prevent loss of grain, the capacity of the 8t grain trailers with whole crop silage which has an unsettled density of about 0.1 t/m^3 will be 2.3t. The separation of the grain/straw mixture at the farmstead will need the supervision of one man so that only one man remains to carry out the transport. Allowing 3 minutes to unload at the farmstead and 1 minute to hitch/unhitch the trailer, the farm transport model(37) predicts the system will achieve a workrate of 2.20 h/ha. This can be reduced to 1.99 h/ha if only one minute is taken to unload; the trailer being the limiting part of the system.

An alternative procedure to assist the transport system is for the harvester to take the trailer to the farm gate to meet the transport tractor. This alternative reduces the time needed to 1.92 h/ha. This represents the best workrate that could be achieved by the system. A more likely estimate allowing for a 70% work efficiency factor is 2.76 h/ha.

5.2.4.3 Proposals B/C workrate

The last two proposals involve making a silage with urea and eliminate the separation operation at harvest. Some system will be needed to add the urea and prepare the silo which may be a traditional bunker silo or 'plastic sausages'. For example, the trailer may be tipped into a dumpbox. However it is unlikely to require the continuous attention of one man and so the system is proposed to consist of a 2 man transport team but spending 5 minutes unloading. This achieves a workrate of 1.42 h/ha. As before allowing for 70% work efficiency, an estimate of overall workrate is 2.03 h/ha.

5.2.5 Machinery

All the proposals require additional machinery, but these fixed costs are deliberately excluded from the model. The increase in total farm gross margin can then be compared with the cost of this machinery. This increase will already include the saving on the combine and the baler and the additional cost of a contractor to harvest the rape and beans.

The combine system has available grain storage, grain drier and straw storage. The latter could be stacked outdoors covered with plastic but the costs are similar.

5.2.5.1 Proposal A

The grain store is still required. Additional equipment is needed to separate the grain and straw and to add urea to the straw that is not dried. The drier should be replaced by one using straw, which must also be capable of drying rape and beans. The straw storage would be sufficient in volume for the chopped straw but is unlikely to be suitable for urea-treated chopped straw silage. The wall pressure should be considerably less than with grass silage as it is much drier and less dense even when settled. However it is unlikely it could be stored as high as bales of straw.

5.2.5.2 Proposal B

Assuming a storage height of 2m and a density of 0.1 t/m^3, the produce from 154 ha of wheat will cover an area of 1 ha! The density when compressed in storage is likely to be 0.17 t/m^3, i.e. 262 ha per hectare of storage. Plastic sausages are thus the only feasible alternative on this scale and these are likely to have an annual cost £2/t for the 'sausage' and another £2/t for the equipment to fill the 'sausage'. There will also be the loss of crop from one hectare but this costs only about £300/ha, the marginal value of land, and is negligible. The grain and straw storage is thus not needed, except perhaps to store the plastic for the 'sausage'. The grain drier is needed to dry the rape and beans on the cereal farm.

5.2.5.3 Proposal C

Similar comments apply as to proposal B but in this case there is an additional need for equipment to separate the grain and straw. The equipment could be based at a central facility to which the mixture is transported. The cost of transport is however high for the low density grain/straw mixture. In addition the straw may need to be returned to the farmstead to be fed to the livestock, but this need not present an additional cost if the vehicle travelling to the farm carries the straw.

An alternative is a mobile separator which travels round the farms so that the straw remains at the farmstead and only the grain is transported. Compared with a transport cost of £12/t for a 10 mile journey, this is almost certain to be more economic.

In either case, if the straw is used on the farm, its delivery must be tailored to its use, if the need for storage for the separated straw is not to be required.

5.3. Results

Replacing the harvesting and barley operations by whole crop harvesting in the farm model as detailed above, the farm gross margins for the different configurations are:

	Conv	A	B	C
	-	-	(72477)	(73150)
Cereal farm	70232	82588	78566	80109
	-	(94538)	(83388)	(86011)
	-	-	(84937)	(86793)
Grass/cereal farm	77646	90975	87517	89477
	-	(98338)	(90416)	(92912)

The figures in brackets are the values obtained if the harvesting workrate is 70% more and less than the most likely value estimated above. It is immediately apparent that the grass farm is less sensitive to the workrate.

The farm gross margin is composed of the crop gross margins less the cost of men and field machinery, fuel and repair costs and penalties due to rotation and lack of timeliness.

An interesting comparison on the cereal farm, which is only harvesting the straw in order to sell it, is the farm gross margin if the straw is burnt in the field. This is £76,693. It is considerably higher than if the straw is baled and sold at £22.5/t. The straw needs to be sold at £31.2/t to break-even, all else being equal. Burning was assumed to take 1.06 man h/ha and have no other effect, positive or negative. This and the alternative of straw incorporation should be borne in mind in comparing the new proposals with the existing system on the cereal farm, which assumes barley.

Solutions were also calculated for different soil types but although the level of farm gross margin changed, the difference between the proposals and the conventional system was altered very little and so the effect of land type can be neglected.

5.3.1 Proposal A

This proposal increases farm gross margin by £12,356 on the cereal farm (but only £5,985 over burning) and by £13,329 on the grass farm. This has to be sufficient to pay for equipment to separate the grain and straw and a drier. Taking a 10 year life and 3% annual maintenance charge, the capital costs which can be justified by the saving are £72,257 (£34,474) and £77,947. This gives some scope for developing a farmstead system of grain separation and drying.

An alternative analysis is to estimate the cost of the machinery likely to be required:

1) An equivalent to a novel separation system is the separation section of a combine harvester of 8 t/h straw throughput. This might cost £40,000, annual use 250 hours, life 10 years, giving an annual cost of £8,280 (grass farm: 125h, £6,040).

2) Grain drier for grain/straw using straw as fuel. This might add £10 per t dried to the drier cost, say £20,000. The life would be maybe 20 years, 3% annual maintenance giving an annual cost of £3,280 (grass farm: £10,000, £1,640).

3) Plastic 'sausages' for half the straw treated with urea at £2/t is approximately £1,000 per annum (grass farm: £500). It is assumed that half is dried and available for use as bedding.

Assuming other costs are negligible within the error in the above estimations, the net increase in profit from proposal A becomes £-204 (£-6665 versus burning) and £5,149 respectively on the cereal and grass farms. In other words, the scale of equipment required is likely to eliminate the apparent savings on a cereal farm. There is however considerable scope for developing suitable equipment which is cheaper.

On a grass-cereal farm there remains an increase in profit of £5,149 even after these assumptions, which indicates that the proposal has considerable scope on the type of farm.

5.3.2 Proposal B

The proposal increases farm gross margin by £8,334 (but only £1,873 over straw burning) on a cereal farm and by £9,871 on a grass farm. The major need is for the storage system, estimated at £4/t. This is an annual cost of £6,690 and £4,180 respectively. On the cereal farm there will be an additional saving for a (smaller) drier for the non-cereal crops, say £10,000, giving an annual cost of £1,640. On the livestock farm the drier will be saved altogether which will give a similar saving.

On the livestock farm, bedding will need to be purchased. 0.20-0.40t straw/cow winter would typically be required with a slurry system though alternatives such as sawdust and sand are possible. At £30/t delivered and assuming 1.9 cow equivalents per hectare (cows and followers), this will cost £1,140-2,280 per annum. A non-slurry system would require at least double this.

The resulting net profit changes are £3,284 on a cereal farm and £5,051-6,191 on a grass-cereal farm. The proposal is probably untenable on a cereal farm where there would be an additional loss of profit due to the need to transport the feed to a nearby farm, as the above profit only allows £1/t for transport of the bulky produce. The proposal is however attractive where there are livestock, even at double the cost of bedding.

5.3.3 Proposal C

The proposal increases farm gross margin by £9,877 on the cereal farm and £11,831 on the livestock farm. As for proposal B, storage costs £6,690 and £4,180; drying saves £1,640; bedding costs £1,140-2,280. This leaves £4,827 and £7,011 respectively. Separation costs might be of the order of £2/t for a large scale system - for example a machine travelling round to the farms in the 'co-operative'. This amounts to £6,350 on the cereal farm and £2,540 on the livestock farm, resulting in a net profit of £-1,523 and £4,471 respectively. Alternatively a capital cost of £25,000 and £36,700 could be justified on separation equipment (10 year life, 5% annual maintenance). Note that on the cereal farm there would be an additional extra transport cost for the loose chopped straw.

5.3.4 **Summary of net profitability of proposals**

The estimates of profitability described above (excluding increased transport costs on the cereal farm) are:

Proposal		Cereal Farm	Livestock Farm
A	Dry	-204 (± 6328)	5149 (± 4208)
B	Feed	3284 (± 6922)	5051 (± 4459)
C	Industry	-1523 (± 6458)	4471 (± 3799)

These results clearly indicate that a large scale combine harvesting system including other non-cereal combinable crops, benefits little from whole crop harvesting. Where combining is a small part of the farm and there are no other combinable crops, all the systems are likely to be profitable.

Assume a 25% error on all value estimates. In the case of feed value this is the error in the ME increase. Thus the increase in value of urea treated straw is worth £4.5/tDM less and urea treated whole crop is worth £3.6/tDM less. The separation equipment for proposal A costs £10,000 more, etc. The effect on the analysis is shown in brackets. There is surprisingly little difference between the sensitivity of the proposals because where there is a large unknown in the equipment the product values are well established and vice-versa where there is little equipment, a small change in feed value increases the sensitivity. It is worth noting that the highest sensitivity comes mainly from changing the feed value of whole crop silage from £80.8/t to £77.2/t, which is a very small change.

5.4 Conclusion

A 250 ha combinable crops farm and a 200 ha grass-cereal farm (half cereal) were analysed. Land type was shown not to affect the comparisons.

The proposal for whole crop harvesting with drying and separation at the farmstead, leading to conventional dry grain for sale, allows a capital expenditure on the farmstead equipment of over £70,000. Estimates of the likely equipment needed suggest negligible difference in profit in the end on the cereal farm but a profit increase of £50/cereal ha on the livestock farm.

The proposal for whole crop cereal silage preserved with urea and fed to cattle, is insufficiently profitable to pay for the increased transport costs on the cereal farm. On the livestock farm profit increases by £50/cereal ha, even after allowing for the purchase of bedding. Additional livestock will be needed.

The proposal for whole crop cereal preserved with urea and used for industrial purposes, is insufficiently profitable to pay for separation costs on the cereal farm. On the livestock farm profit is increased by £45/cereal ha.

The results clearly show that the value of whole crop harvesting comes from the saving of the combine harvester on a relatively small cereal area on which a forage harvester is already available plus the availability of adjacent livestock.

A 25% error in estimates of value was sufficient to eliminate the savings. In particular reducing the value of whole crop cereal silage from £80.8/t to £77.2/t.

6. Discussion

There is considerable natural variability between crops and situations and this has to be accepted. However there are several areas where the difficulty of making comparisons is compounded by the lack of information.

The value of straw or whole crop silage depends on both its metabolisable energy and its intake. There are some difference apparent in in-vivo and in-vitro results. Predictive systematic estimates of intake are almost negligible in spite of a considerable quantity of experimental measurements. There is a need to develop methods of predicting straw intake from measurable crop characteristics even if only relative between types of straw. Similar comments apply to silage. A change in value of only £3/t can make or break the profitability of whole crop silage.

Grain losses when combining can have a major impact on profitability but they are only well studied for wheat, barley and oats. More information is needed on threshing, header and shedding losses in crops such as oilseed rape, beans and peas, and their effects on limiting combine speed.

This study has neglected second-order effects on the profitability of the systems, which should be small in comparison to estimation error of the main effects. Thus whole crop harvesting may have beneficial weed control effects as the total above ground mass is removed from the field. The grain stripper may have an impact on the grain drying system though the results suggest the optimum throughput is not as much greater as has been suggested. There is a need to develop methods for analysing the optimum harvesting strategy with regard to the drier capacity, drying costs and the autumn workload in order to be able to fairly compare alternative systems.

7. References

1. Orskov, E.R.; Shand, W.J. *The effect of type and variety of cereals on nutritive value of straw.* Pira International Conference: Straw - A valuable raw material, Cambridge, 27-29 October 1987.

2. Staniforth, A.R. *Cereal straw.* Clarendon Press, Oxford, 1979.

3. Audsley, E. *The effects of field burning restrictions, straw incorporation and alternative uses as fuel, fibre or feed on the amount of field burning and the supply and demand for straw and the economic consequences on the farm of baling, incorporation and briquetting.* AFRC Engineering Report No. 52, Silsoe, Bedford, 1987.

4. Alderman, G. *Feeding value of cereal straw.* Report on Straw Utilisation Conference. MAFF/ADAS, Oxford, 1976.

5. Audsley, E. *An arable farm model to evaluate the commercial viability of new machines or techniques.* Journal of Agricultural Engineering Research, 1981, 26 (2), 135-149

6. *DRIER: Cost of high temperature grain drying.* User documentation, Operational Research Group, AFRC Institute of Engineering Research, Silsoe, Beds. December 1986.

7. *NEARAM: Near ambient grain drying simulation.* User documentation, Operational Research Group, AFRC Institute of Engineering Research, Silsoe, Beds. July 1988.

8. Audsley, E.; Wheeler, J.A. *The annual cost of machinery using actual cash flows.* Journal of Agricultural Engineering Research, 1978, 23, 189-201

9. Hobson, R.N.; Price, J.S.; Tuck, C.R.; Neale, M.A.; Hale, O.D.. DN 1443 *Evaluation and development of the grain stripping header system.* Divisional Note 1443, AFRC Institute of Engineering Research, Silsoe, 1986.

10. *Stripper Harvesting Stripping away combine costs.* Presentation paper at the power farming/ICI conference "Cereals-high yields with less labour" 28th January

11. de Jong, G.J., Zelhorst, L. *The relationship between time of harvesting and yield of cereals.* Internal Report No. 265, National Service for the Ijsselmeerpolders Scientific Division Kampen 1971.

12. Audsley, E.; Boyce, D.S. *A Method of minimising the cost of combine harvesting and high temperature grain drying.* Journal of Agricultural Engineering Research, 1974, 19, 173-188

13. *Power Farming, October 1988.*

14. Nyborg, E.O. *A Test Procedure for determining combine capacity.* Canadian Agricultural Engineering, Vol 6, Number 1, 1964

15. *Test reports for users 1962-1970. National Institute of Engineering Research, Silsoe.*

16. Wrublesky, P.D.; Smith, L.G. *Separation characteristics of conventional and non-conventional grain combines.* American Society of Agricultural Engineers, Paper No. 78-156, 1978

17. Klinner, W.E. *Reducing field losses in grain harvesting operations.* The Agricultural Engineer, Vol 34, Spring 1977.

18. Reed, W.B.; Zoerg, G.C. *A laboratory study of straw walker efficiency.* American Society of Agricultural Engineers, Paper No. 72-638, 1972

19. *Axial flow combine harvester.* MAFF Booklet 2375, 1981

20. Speiss, E. *Comparative trials with an axial flow combine harvester.* Journal of Agricultural Engineering, February 1981

21. Arnold, R.E. *Rotary Combine Harvesters.* Conference: Cereal Harvesting - Methods and Machines. National Agricultural Centre, Stoneleigh, 6th February 1980.

22. Boyce, D.S.; Rutherford, I. *A deterministic cost model -total combining costs machine costs and crop losses over a range of operating conditions,* Divisional Note DN/SY/112/1955, National Institute of Agricultural Engineering, Silsoe, 1971.

23. Dobbs, M.E. and Petton, W.L. *Theoretical Effect of Weather factors on the Kernal Moisture of a standing crop of wheat.* Agronomy Journal, Volume 59, March-April 1967

24. van Elderen, E; van Hoven, S.P.J.H. *Moisture Content Of Wheat In The Harvesting Period.* Research Report 5, 1973. Institute of Agricultural Engineering and Rationalisation, Wageningen, The Netherlands.

25. Hughes, P.G. *Fate of cereal straw - 1976.* Report on Straw Utilisation Conference, Oxford, 24-25, February 1977

26. Orskov, E.R.; Reid, G.W., Kay, M. *Prediction of intake by cattle for degradation characteristics of roughages.* Anim. Prod. 1988 46 29-34

27. *HGCA Grain Haulage Costs 1988.* Marketing Note Vol. 23, issue 21 (10), 21 November 1988.

28. Manley, A.C.; Wood, R.S. *The analysis of fraction of cereal crops on three dates prior to harvest.* Agricultural Progress Vol. 53, 1978

29. Everett, J.; Rutherford, I; Dumont, A. *A study of the quantitative changes in grain yield with time in spring barley, 1971.* NIAE Note 52, West Park, Silsoe, May 1972.

30. Boyd, J.E.L.; Longmuir, A. *Whole crop harvesting of cereals in Scotland.* Agricultural Engineer, Autumn 1983.

31. Wilton, B. *Whole crop cereals : harvesting, drying and separation.* Agricultural Engineer, Spring 1978

32. *Research Investigations and Field Trials 1983-4.* School of Agriculture, Aberdeen, April 1985

33. Ramanzin, M.; Orskov, E.R.; Tuck, A.K. *Rumen degradation of straw 2. Botanical fractions of straw from two barley cultures.* Animal Production 1986 43 271-278

34. Doyle, C.J.; Mason, V.C.; Baker, R.D. *Economics of straw uses in UK.* Biological Wastes 23 (1988) 39-56

35. Audsley, E. *Predicting ruminant dry matter intake from degradation characteristics using mathematics.* Divisional Note DN 1472, AFRC Institute of Engineering Research, Silsoe, June 1988

36. Mason, V.C.; Tetlow, R.M. *Whole-crop wheat as conserved feed for beef production.* In Proceedings of International Conference on Straw - a valuable raw material, Vol. 3, Cambridge, 27-29, October 1987.

37. Foote, N. *A mathematical model to predict the field performance of farm vehicles.* Divisional Note DN 1142, AFRC Institute of Engineering Research, Silsoe, 1982.

Appendix 1

Data used in the analysis

Crop Data

The crop data are given below as a table for each crop showing the sequence of operation required. The columns of the table are as follows:

The 'start' and 'end' times of each operation are specified by a letter code for the month and the week number.

Month	Week	Code
January	1-4	J
February	5-8	F
March	9-13	H
April	14-17	P
May	18-21	M
June	22-26	U
July	27-30	Y
August	31-34	A
September	35-39	S
October	40-43	O
November	44-47	N
December	48-52	D

Thus A4 means the fourth week of August.

The 'machinery' are the machine numbers from the machinery table, L for labour. Where more than one of machine type n is needed this is indicated as m*n. Thus 9+2*1+3*L means a combine, two tractors and three men.

The 'hours' are expressed as a percentage of the available hours for ploughing which are given in the workable hours table.

The 'timeliness penalties' are shown in figures 1a-c indicated by the given letter.

Operation	Start	End	Machinery	Workrate h/ha	Hours %	Timeliness Penalty
Crop: Winter Wheat	**Gross Margin: £710/ha**					
Spread PK	A4	N1	2+1+L	0.59	100	
Plough	A4	D4	1+8+L	2.38	100	
Power Harrow	S2	D4	1+3+L	1.69	80	
Seedbed cults	S4	D4	1+L	0.34	70	
Plant	S4	D4	4+1+L	0.84	70	a
Spray	N2	H4	5+1+L	0.41	60	b
Roll	H5	P2	1+2	0.41	80	
Fertilise	H5	P4	6+1+2	0.41	100	
Spray	H5	P4	5+1+L	0.41	60	
Combine	A4	S3	9+2*1+3*L	0.98	70	c
Bale straw) or	A4	S5	7+3*1+3*L	0.93	70	
Burn straw)	A4	S5	L+1	1.06	70	
Crop: Winter Barley	**Gross Margin: £580.5/ha**					
Spread PK	A4	N1	2+1+L	0.59	100	
Plough	A4	D4	1+8+L	2.38	100	
Power Harrow	S2	D4	1+3+L	1.69	80	
Seedbed cults	S4	D4	1+2	0.34	70	
Plant	S4	D4	4+1+L	0.84	70	a
Spray	N2	D4	5+1+L	0.41	60	
Spray	N2	H4	5+1+L	0.41	60	b
Fertilise	H1	H4	6+1+L	0.41	100	
Roll	H5	P2	1+21	0.41	100	
Spray	H5	P4	5+1+L	0.41	60	
Combine	Y4	A3	9+2*1+3*L	0.91	70	c
Bale straw	Y4	S1	7+3*1+3*L	0.76	70	c
Crop: Oilseed Rape	**Gross Margin: £488.0/ha**					
Heavy cults	Y4	S5	1+L	1.38	100	
Seedbed cults	A2	S5	1+L	1.19	80	
Plant	A2	S5	4+1+L	0.84	80	a
Spray	O3	N4	5+1+L	0.41	60	
Fertilise	F2	F4	6+1+L	0.41	100	
Fertilise	H1	H4	6+1+L	0.41	100	
Combine	Y4	A3	9+1+2*L	1.53	70	c
Burn straw	Y4	S5	L+1	1.06	70	
Crop: Spring Beans	**Gross Margin: £406.5/ha**					
Plough	O1	D4	1+8+L	2.38	100	
Base fertiliser	F2	P2	2+1+L	0.59	100	
Power harrow	H1	P2	1+3+L	1.69	80	
Seedbed cults	H1	P2	1+L	1.19	80	
Plant	H1	P2	4+1+L	0.84	80	a
Spray	H5	P4	5+1+L	0.41	60	
Spray	M1	M3	5+1+L	0.41	60	
Spray	U4	Y1	5+1+L	0.41	60	
Combine	S4	O2	9+1+2*L	1.53	70	c

Operation	Start	End	Machinery	Workrate h/ha	Hours %	Timeliness Penalty
Crop: Spring Barley **Gross Margin: £538.1/ha**						
Plough	O1	D4	1+8+L	2.38	100	
Base fertiliser	F2	P1	2+1+L	0.59	100	
Seedbed cults	F2	P1	1+L	1.19	80	
Plant	F2	P1	4+1+L	0.84	80	b
Spray	M2	M3	5+1+L	0.41	60	
Combine	A4	S3	9+2*1+3*L	0.77	70	c
Bale straw	A4	S5	7+3*1+3*L	0.65	70	
Crop: Silage **Area: 100 ha**						
Fertilise	H1	H4	6+1+21	0.41	100	
Silage-1	M4	U2	10+3*1+3*21	1.31	100	
Silage-2	U5	Y3	10+3*1+3*21	0.72	100	
Silage-3	A2	S1	10+3*1+3*31	0.72	100	
Crop: Drill grass **Area: 38.3 ha**						
Plough	A4	S3	1+8+L	2.38	100	
Power harrow	A4	53	1+3+L	1.69	80	
Seedbed cults	A4	S5	1+L	1.19	80	
Plant	A4	S5	4+1+L	0.84	80	

Workable hours (Rainfall 0.59m, soil type 1.5)

Weeks	Available hours for ploughing
1-4	0
5-8	19
9-12	113
13-16	216
17-20	269
21-24	269
25-28	269
29-32	267
33-36	254
37-40	207
41-44	144
45-48	81
49-52	20

Machinery

		Capital Cost	Replacement Interval, Yrs
1	Tractor 60kW	15093	5
2	Trailed fertiliser spreader	3000	7
3	Power harrow	4000	4
4	Drill	5000	7
5	Sprayer	7500	7
6	Mounted fertiliser spreader	1500	7
7	Baler	5200	7
8	Plough	3573	10
9	Combine	67333	7
10	Forage harvester	12000	7
L	Labour	9000	(annual cost)

Rotation Matrix, reduction in gross margin, £/ha

Cereal Farm

			after			
	WWheat I	WWheat	WBarley	OSRape	SBeans	Max area
WWheat I	*	*	90	0	0	-
WWheat	90	122	*	*	*	-
WBarley	73	73	73	*	0	-
OS Rape	0	0	0	*	*	62.5
SBeans	0	0	0	0	*	50.0

Livestock Farm

			after			
	WWheat I	WWheat	WBarley	SBarley	Grass	Max area
WWheat I	*	*	90	90	0	-
WWheat	90	122	*	*	*	-
WBarley	73	73	73	73	66	-
SBarley	62	62	62	62	28	-
Grass (3 year ley)	0	0	0	0	*	-

(* = not permitted)

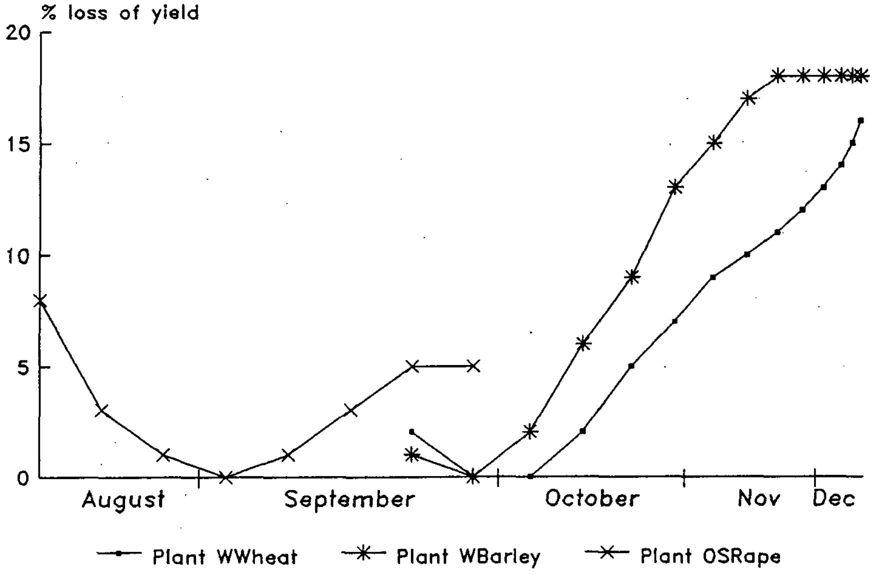


Fig. 1a Timeliness penalties - autumn sowing

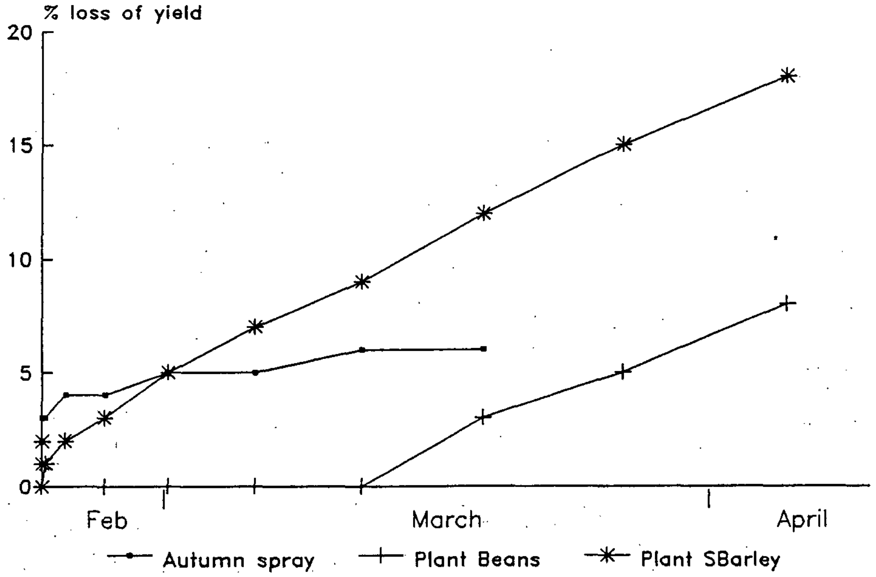


Fig. 1b Timeliness penalties - spring

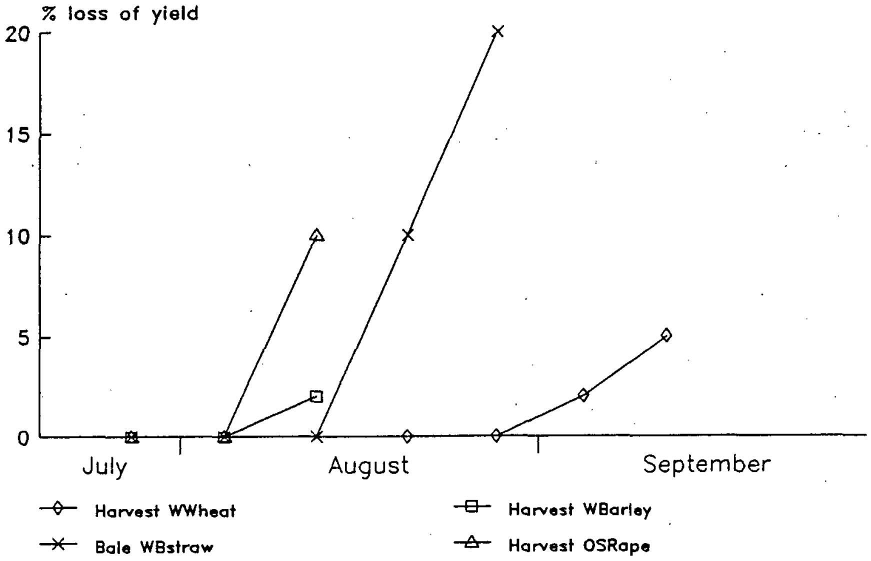


Fig. 1c   Timeliness penalties - harvest

Appendix 2

Example of solution (11t/h combine, 60kW tractor, basic data)

```
         Value of 1hr:1x11t/h+60kW,med
---------------------------------------------------------------------------

  Solution Value:     64198.   in   16 iterations - status Optimal


                             CROPPING
    Crop     Area,ha   Net gross margin  Marginal cost
 1 WWheat-p    94.6              497.2          0.0
 2 Barley-w    42.9              446.6          0.0
 3 Oilseed.    62.5              438.9          0.0
 4 Beans-sp    50.0              345.4          0.0

Value of 1 ha more land                       279.5
Value of 1 ha more of crop types:
     79.3  Oilseed.
      1.2  Beans-sp



Workplan: WWheat-p
               % of crop in each period
Operation  F2 H1 H5 P3 M1 M4 U4 Y2 Y4 A2 A4 S2 S4 O1 O3 N2 D1
 1 Spread.P                               51  0  0  9 39
 2 Plough20                                4 18  0 31 39  8  0
 3 Power.Ha                                  12  0 41 39  8  0
 4 Seedbed.                                     8 45 39  8  0
 5 Plant.WW                                     8 45 39  8  0
 6 Spray...  0  0                                       100  0
 7 Roll....      100
 8 Fertilis      100  0
 9 Spray...      100  0
10 Combine.                               73 27
11 Burn.str                               21 79  0

Workplan: Barley-w
               % of crop in each period
Operation  F2 H1 H5 P3 M1 M4 U4 Y2 Y4 A2 A4 S2 S4 O1 O3 N2 D1
 1 Spread.P                                0 58 41  0  0
 2 Plough20                                0 58 41  0  0  0  0
 3 Power.Ha                                  58 41  0  0  0  0
 4 Seedbed.                                     100  0  0  0  0
 5 Plant.WB                                     100  0  0  0  0
 6 Spray...                                              29 71
 7 Spray...  0  0                                        29 71
 8 Fertilis   100
 9 Roll....      100
10 Spray...      100  0
11 Combine.                         38 62
12 Bale.WBs                         38 62  0
```

```
Workplan: Oilseed.
               % of crop in each period
Operation  F2 H1 H5 P3 M1 M4 U4 Y2 Y4 A2 A4 S2 S4 O1 O3 N2 D1
 1 Heavy.Cu                          0 69 31  0  0
 2 Seedbed.                            69 31  0  0
 3 Plant.OS                             0100  0  0
 4 Spray-Oc                                             100  0
 5 Fertilis100
 6 Fertilis   100
 7 Combine.                         86 14
 8 Burn.str                          0100  0  0  0

Workplan: Beans-sp
               % of crop in each period
Operation  F2 H1 H5 P3 M1 M4 U4 Y2 Y4 A2 A4 S2 S4 O1 O3 N2 D1
 1 Plough.(                                            0  0 61 39
 2 Base.Fer 14 86  0
 3 Power.Ha   100  0
 4 Seedbed.   100  0
 5 Plant.SB   100  0
 6 Spray...      100  0
 7 Spray...            100
 8 Spray...                  100
 9 Combine.                                     79 21


Derivation of net gross margins

    WWheat-p  94.6ha Input gross margin   54808.
                     less costs:-      Data   Fuel+Repairs
                          ROTATION       0.
                          Spread.P       0.        109.
                          Plough20       0.        989.
                          Power.Ha       0.        679.
                          Seedbed.       0.         72.
                          Plant.WW    3110.        238.
                          Spray...       0.        131.
                          Roll....       0.         87.
                          Fertilis       0.         52.
                          Spray...       0.        131.
                          Combine.     400.       1567.
                          Burn.str       0.        225.
Net gross margin - total                                        47017.
Net gross margin - £/ha                                           497.
```

```
    Barley-w  42.9ha Input gross margin   23616.
                     less costs:-     Data   Fuel+Repairs
                          ROTATION    1750.
                          Spread.P       0.        49.
                          Plough20       0.       449.
                          Power.Ha       0.       308.
                          Seedbed.       0.        33.
                          Plant.WB     142.       108.
                          Spray...       0.        59.
                          Spray...       0.        59.
                          Fertilis       0.        24.
                          Roll....       0.        40.
                          Spray...       0.        59.
                          Combine.     341.       657.
                          Bale.WBs     106.       255.
Net gross margin - total                                       19176.
Net gross margin - £/ha                                          447.

    Oilseed.  62.5ha Input gross margin   30500.
                     less costs:-     Data   Fuel+Repairs
                          ROTATION       0.
                          Heavy.Cu       0.       194.
                          Seedbed.       0.       167.
                          Plant.OS     230.       157.
                          Spray-Oc       0.        86.
                          Fertilis       0.        35.
                          Fertilis       0.        35.
                          Combine.     198.      1817.
                          Burn.str       0.       149.
Net gross margin - total                                       27432.
Net gross margin - £/ha                                          439.

    Beans-sp  50.0ha Input gross margin   20325.
                     less costs:-     Data   Fuel+Repairs
                          ROTATION       0.
                          Plough.(       0.       523.
                          Base.Fer       0.        58.
                          Power.Ha       0.       359.
                          Seedbed.       0.       134.
                          Plant.SB       0.       126.
                          Spray...       0.        69.
                          Spray...       0.        69.
                          Spray...       0.        69.
                          Combine.     195.      1454.
Net gross margin - total                                       17270.
Net gross margin - £/ha                                          345.
```

Men and Machinery

	Name	Number	Annual cost
1	TRAC60	2.4	8443.
2	TrldFert	0.2	113.
3	Pow.Harr	0.9	859.
4	Drill	0.5	422.
5	Sprayer	1.2	1539.
6	Mtd.Fert	1.4	350.
7	Baler	0.2	229.
8	Plough	1.3	707.
9	Combine	1.0	11142.
21	REGULAR	2.5	22892.

Appendix 3

Derivation of threshing loss equation

Assume that the rate at which grain is separated from the material other than grain (MOG) is a constant, which is a function of the thickness of the straw mat. The probability distribution is then the negative exponential distribution and the amount of grain separated as it passes through the combine is given by the formula $T\lambda\exp(-\lambda x)$ where T is grain throughput :

Let the length of the separating mechanism be L, then losses, G, are those grains which will emerge after L:

$$\int_{L}^{\infty} T\lambda\exp(-\lambda x)dx = T\exp(-\lambda L)$$

As more straw passes through the combine, the rate at which grain can become separated appears to reduce pro-rata. In other words if the straw is twice as thick it takes the grain twice as long to pass through it. However if the width of the separating area is increased the straw thickness is reduced. Thus $\lambda = \gamma W/S$ where S is straw throughput, W width and γ a constant. The loss as a proportion of grain throughput thus becomes $\exp(-\gamma LW/S)$

The specific straw throughput, $s = S/LW$, and is the straw throughput per unit area of the straw walkers. Straw walker area is representative of the separating area since the sieves should be in proportion to them. Also allow for some grains to be lost through other causes (a), for example unthreshed heads and for only a proportion of the grain to need separating (b). The formula then becomes $a + b\exp(-c/s)$ where a, b, c are constants to be estimated.

Example