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RESEARCH ON THE USE OF CEREAL STRAW

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by

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Final report of a nine month project by Mr A R Staniforth which was submitted on behalf of the Straw Utilisation Working Group. The work commenced in September 1991 and was funded by a grant of £14,300 from the Home-Grown Cereals Authority (Project No. 0055/2/91).

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1. INTRODUCTION

1.1 This review of research on cereal straw has been carried out on behalf of the Straw Utilisation Working Group. This is a group made up of farming interests, the straw trade and researchers and specialists in straw use, which evolved from a group originally set up by the Minister of State for Agriculture; it has more recently been sponsored by the National Farmers Union.

1.2. Two circumstances make this an appropriate time to carry out the review. The first is that the field burning of straw and stubble will be banned in the United Kingdom from 1993. The second is that financial margins from cereal growing are under pressure and there is a need to find profitable outlets for the by-product, straw.

1.3. The information in this report has been gathered mainly from a search of published data. This has involved scrutiny of several thousand references contained in a number of databanks, including those of CAB International, Dialogue Agricola, The Food and Agriculture Organization of the United Nations (FAO), the Research Association for the Paper and Board, Printing and Packaging Industries (PIRA) and the Bath Information Data Service (BIDS).

1.4 The search has been limited in the main to databanks covering the past twelve years. Information relating to straw utilisation prior to that has already been researched and reported upon in a number of publications listed in section 1.11.

1.5 Many of the items listed in the databanks refer to straw as a feeding stuff or to straw incorporation in the soil. These aspects are considered only partially in the present review. A full up-dating of information on the nutritional aspects of straw, as a feed for ruminants, is to be published as HGCA Research Review No. 24 by Dr. Ian Givens in late 1992. Agronomic aspects related to straw incorporation have already been covered in HGCA Research Review No. 11, entitled "Changing Straw Disposal Practices", edited by Dr. R.D. Prew and Dr. B.D. Smith.

1.6 The purpose of this document is to review knowledge and research about the many possible uses of straw. A high proportion of the references are derived from Europe and North America. However, much interesting research is also carried on in Asian countries - notably China, Japan and the Indian sub-continent. There are, too, valuable references to work in Australia, Africa and South America which need to be considered. Some of the work refers to rice straw but is nevertheless relevant to all cereal straw producers and users. There are also references in the databanks to the straw/haulm of oil seed rape and linseed. These are, strictly, outside the scope of this review and will only be mentioned in passing.

1.7 For British cereal growers the aim is to sell as much as possible of the straw which is at present surplus to need, at an economic price. There are scores of actual and potential outlets for quantities great and small. Among current uses, archery targets take up only tens of tonnes; others such as turkey litter, hundreds of tonnes; thatching, thousands and compost and carrot covering, hundreds of thousands of tonnes. Potential future uses vary from algal control, which could take a few hundred tonnes, to the manufacture of chemicals or paper which could use hundreds of thousands of tonnes. This review covers a very wide range of uses. It is impossible to consider them in detail and only brief comments are included in the text.

1.8 The author would like to acknowledge the help received over many years from Thomas R. Miles, consulting engineer of Beaverton, Portland, Oregon. He was the organiser of the "First World Straw Conference" in Eugene in 1974 and has continuously provided information about straw use in North America. A number of

references in this review are derived from this source.

1.9 Whenever possible the most interesting references in the databanks have been followed up by consulting the original papers in the Radcliffe Science Library in Oxford, in Reading University Library or in the library of the Silsoe Research Institute. In some cases it has been necessary to obtain originals from the British Library through CAB International. All these institutions have been most helpful.

1.10 Almost all the references which are mentioned in the text are listed alphabetically at the end of this review. These publications themselves carry further references which will add to readers' knowledge of the subject.

1.11 Earlier reference works of a general nature:

Report of the First World Straw Conference. 1975. Thomas R. Miles, Beaverton, Portland, Oregon, USA.
Les Pailles de Céréales. 1976. ITCF/APRIA, 8. Avenue du Président Wilson, 75116, Paris.
Cereal Straw. 1979. A.R. Staniforth, Oxford University Press, High Street, Oxford.
Agricultural Residue Management - A Focus on Rice Straw, University of California Agricultural Engineering Department, Davis, California, 95616.
Utilisation of Agricultural Crop Residues, 1978. An Annotated Bibliography of Selected Publications. 1966-76. Agricultural Research Service, U.S.D.A., Western Region, 2850 Telegraph Avenue, Berkeley, California 94705.
Reports on Straw Utilisation Conferences at Oxford, 1974, 1978, 1980, 1982, 1984. MAFF. London.
Perspectives Agricoles - Spécial paille. 1980. Paris.

2. STRAW - THE RAW MATERIAL

Yield

2.1 There is a dearth of accurate information about current straw yields in the UK. It is many years since the National Institute of Agricultural Botany (NIAB) weighed the yield of straw from the varieties tested in its experimental plots. The procedure was time-consuming and as straw came to be considered of comparatively little value, it was decided that only grain yields would be assessed.

2.2 The Ministry of Agriculture Fisheries and Food (MAFF) for some years included a question on straw yield in its December quarterly census, but has not done so since 1982. ADAS carried out a number of field determinations of straw bale weights and numbers per ha in 1975, 1976 and 1977 (MAFF, 1984), but these systematic attempts to establish yields have not been continued.

2.3 Attempts have been made to calculate straw yields by applying estimated average straw:grain ratios, sometimes known as the Harvest Index, to areas of production for which there are reasonably reliable figures for grain yield. The results of these calculations and previous surveys are summarised in Straw Disposal and Utilisation (MAFF, 1984). However, as will be shown below, this can be an unsound practice.

2.4 One of the difficulties in estimating straw yields has been that so-called 'recoverable' yield is different from total straw yield. For instance, recoverable yield is obviously affected by stubble height and there is some scientific information on this point (Smith et al, 1975). Combining method also has an effect, both in the extent to which the straw is battered and in the type of swath that is left for the baler to pick up.

2.5 There are few references in the literature to the effect of combining method on straw yield but one interesting Russian paper describes how differences in 'cohesiveness' of windrows affects the efficiency of pick-up (Satchenko, 1983). It has been reported that up to 20 per cent of the cut straw does not reach the swath from an axial flow combine as compared with 5 per cent or less from combines with a gentler action (Gilbertson and Knight, 1987).

2.6 One of the rare references to straw:grain ratios and to the proportion of straw which is harvested after combining occurs in a North American paper (Allmaras et al, 1985). These research workers, using a 'catch apron', found that the collected wheat straw plus chaff represented a percentage of total straw yield (previously assessed by hand harvesting) varying between 52 and 64. The figures are from 12 separate trial cuts, all except one of the variety Stephens. Grain yield varied between 4.79 and 7.11 t.p.a. Clearly, the yields of straw plus chaff obtained in this trial were greater than would be obtained by baling.

2.7 The conclusion must be that 'recoverable' straw yields - the amount actually baled - may be no more than half the total above ground production of straw.

2.8 Season and cereal variety have an important effect on straw yield. One of the few recent scientific investigations into these factors has been carried out in Northern Ireland (White, 1987). The baled straw yields of a number of barley varieties were measured over three seasons. For a single variety the yield varied by as much as 49 per cent between 1981 and 1982. There were also big differences between varieties. For instance, Inga gave the highest average yield over 3 seasons, at 2.75 t/ha, compared with 1.94 t/ha for Golden Promise. In these Northern Ireland experiments, the straw:grain ratios varied with both variety and season and the author concludes that straw:grain ratio is a poor method of predicting straw yields. This paper summarises by saying that, 'There appears to be no alternative to direct assessment of straw yield of varieties as neither grain yield nor straw length are closely related to straw yield', and goes on to suggest how this could be done.

2.9 The author makes the point that, in Northern Ireland, 'In view of its role in animal enterprises and its value on the market, farmers .... may prefer to grow varieties with high straw production in order to supplement their income from the cereal crop as a whole ..' The same considerations would apply in other parts of the United Kingdom if profitable outlets for straw develop. The Northern Ireland paper concludes that, '...straw yield could be included in the Recommended Lists as an additional characteristic ...'.

2.10 Other Northern Ireland work (Easson, 1984) shows that the timing of nitrogen applications to spring barley can affect straw:grain ratio. Late applications have little effect on grain yield, as compared with seedbed application, but may increase straw yield.

2.11 The need to treat straw:grain ratios with some caution as a guide to straw yield is also mentioned by Hungarian research workers (Balla and Szunics, 1978). They found, in trials between 1974 and 1977, that 'Grain:straw ratio in varieties was markedly influenced by crop year'. American workers (Bauer and Zubriski, 1978) have also investigated straw:grain ratios and have made the point that 'straw:grain ratios are not constant' and that 'data ranging over a wide spectrum of grain yields obtained in the field are needed to establish a meaningful functional relationship between straw:grain ratio and grain yield'.

2.12 Some valuable information on both straw yields and baler performance was given at an international conference at Peterborough in May 1990 (Johnson and Hutchinson, 1990). The Northern Straw Company (NSC) harvested large quantities of straw over 4 seasons as shown in the following table.

NSC HARVEST PRODUCTION FIGURES 1986-1989

	1986	1987	1988	1989
Total Bales	79605	54072	75580	123506
Barley Acreage	5686	3892	7063	8462
Wheat Acreage	2062	19889	20698	26674
Total Acreage	26307	23781	27761	35136
Bales/Acre	3.03	2.27	2.72	3.52

Source: NSC Harvest Database

2.13 The table shows that there can be considerable differences in average straw yield per acre from one season to another. Assuming that the bales weighed 500 kg (all the straw was baled in Hesston bales) the yield per acre varied from 1.14 tonnes in 1987 to 1.76 tonnes in 1989.

2.14 Estimates of the geographical distribution of cereal straw production in England and Wales (for 1984) are shown at Appendix I. Recent results of surveys of straw use and disposal in England and Wales are shown in Appendix II.

<u>Nature of straw - fractions, impurities, structure</u>

2.15 Straw is far from being a homogeneous material. Baled straw contains weed residues, grain and other impurities and some estimates of these components have been made (Wood, 1976). The percentage of grain remaining in straw has also been measured in several countries and has varied from about 0.2 per cent to as high as 1.3 per cent (Dean, 1976). Dust contamination can sometimes be serious - as high as 4 per cent in straw delivered to a pulp mill in Eastern Europe (Dean, 1976).

2.16 The proportion of various fractions - internodes, nodes, leaves and leaf sheaths and ears - has been investigated for different cereals (Muller, 1960; Peterson, 1988; Capper, 1987; Sannasgala and Jayasuriya, 1987). There has recently been considerable interest in the fractionation of straw, since it has appeared that some fractions are better suited than others for purposes such as animal nutrition or paper and board making.

2.17 Detailed work on the proportions of different fractions in rice straw (Sannasgala and Jayasuriya, 1987) has shown large differences between varieties. Other work has shown marked differences in the composition of wheat and barley straws of different varieties (Capper et al, 1988).

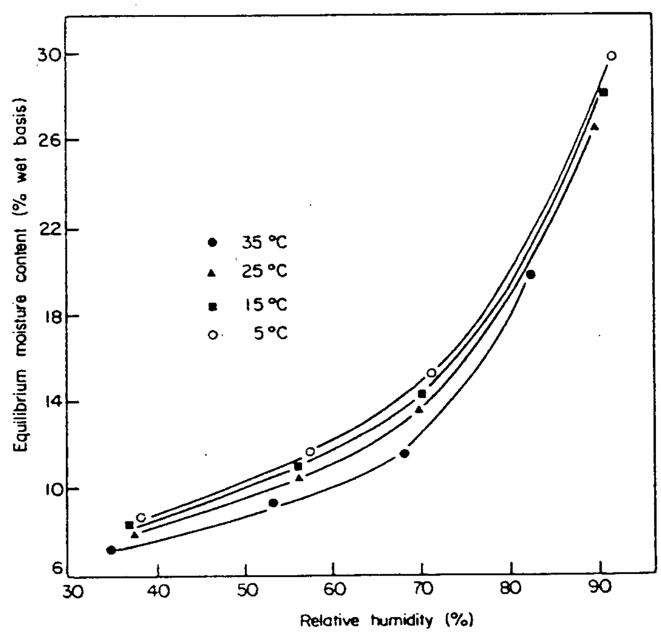
2.18 American work (Smith et al, 1968) showed how the chemical composition of cereal straw varied between fractions, and how important sampling and sample preparation are in determining chemical composition.

2.19 There are marked differences in the structure of straw between species and between varieties. For instance, while barley, oats and some varieties of wheat have hollow-stemmed straw, the stems of some varieties of wheat are 'solid' and contain much pith (Juniper, 1990). A 'solidness' index for wheat stems based on cuts of 4 internodes has been worked out, as a measure of resistance to sawfly (Wallace et al, 1973) - ranging from 4 for fully hollow to 20 for fully solid stems.

Moisture content

2.20 Information available up to 1979 relating to moisture content has been summarised (Staniforth, 1979). More recent work in Germany (Apfelbeck et al, 1990) has shown how different sections of wheat straw dried out over a 14-day period in August. The same workers investigated the rate of in-field drying of the straw left behind the combine after various treatments, and the effect of such treatments on baled straw yields, in both damp and dry harvest seasons.

2.21 Data on equilibrium moisture content-relative humidity relationships for wheat straw, shown in the diagram below (Duggal and Muir, 1981), show rather higher values than those previously given for rice straw (Sain and Broadbent, 1975).



Observed adsorption equilibrium moisture contents of wheat straw. Each point is a mean of 3 replicates

Source: Duggal and Muir, 1981

Potash content

2.22 Some data (Widdowson et al, 1980) indicate an average potash content of around 1 per cent for wheat straw. More recent published data (Withers, 1988) give an average offtake of potash of 9.8 kg per tonne of barley straw (at 85%DM) (0.98%) and 7.5 kg (0.75%) per tonne of wheat straw.

2.23 There is considerable variation in the potash content of straw; rainfall immediately prior to or during harvest tends to reduce potash content. Widdowson et al give the clearest evidence of this reduction, quoting potash contents at Saxmundham varying from a low of 0.7 per cent in a wet harvest to a high of 1.5 per cent in a very dry harvest season.

Phosphate content

2.24 Recent figures given by Withers are at the lower end of some earlier estimates (ITCF:APRIA, 1976), giving an average offtake for both wheat and barley straw of 1.2kg of P_2O_5 per tonne of straw (at 85%DM).

Other chemical contents

2.25 The straws of wheat, barley and wild oats have been analysed for sterol content by research workers in Canada (Thomson et al, 1986). It comes as a surprise that there is a small amount of cholesterol in all these straws - other sterols occur in greater quantities.

2.26 Waxes are also present in straw and analyses have been made in Europe and in Canada (Streibl et al, 1974; Tulloch and Hoffman, 1971; Tulloch and Weenink, 1969). These waxes occur mainly in the leaf fraction and are potentially of economic value.

2.27 Residues of pesticides in straw can have serious consequences - for instance when cucumbers are grown on straw bales. A number of potentially serious residues have been listed (Staniforth, 1979). The analysis of straw for such residues continues to be carried out - for instance in Canada for residues of baytan and bayleton in wheat straw (Ragab et al, 1990). This Canadian work showed that residues of triadimefon from Bayleton spraying could, in some circumstances, be detected in mature straw from the wheat crop.

Influence of variety and soil

2.28 Some interesting work has recently been carried out in France on the analysis of wheat straw, particularly from the standpoint of the paper makers (Molina and Villeneuve, 1991). This work throws some light on the effect of cereal variety and of the soil on which it is grown on the proportions of cellulose, hemicellulose, lignin, ash and silica in the straw. Triticale straw showed up particularly well as a raw material for pulping but the number of samples was low and the report calls for further studies.

2.29 The effect of variety and provenance on the chemistry of straw has been studied recently in Denmark (Petersen, 1988). This work showed clear correlation between the silica content of straw and the nature of the soil on which it was grown.

2.30 Portuguese work (Dias-da-Silva and Guedes, 1990) has also shown that cereal variety and the area in which it is grown can greatly affect straw quality and its nutritive value.

2.31 Other work at the University College of North Wales (Wright and Hughes, 1989) has highlighted the effect on straw quality - in this case spring barley straw - of variety and the site on which the crop is grown. The Home-Grown Cereals Authority Project Report No. 9 covers this work in detail.

3. HARVESTING, MECHANICAL HANDLING AND PHYSICAL TREATMENT

Whole crop harvesting

3.1 Whole crop harvesting of grain and straw, was considered a promising development ten years ago. A 'ways and means' panel report (ADAS:ARC, 1979) concluded that 'Whole crop cereal harvesting can provide new opportunities for cereal growers....'.

3.2 The system, pioneered in Sweden (Claesson, 1977) and researched at Nottingham University (Wilton, 1977; Wilton et al, 1980), was taken forward by the Shell Company in Denmark (Vind, 1984). Field trials have been carried out in the United Kingdom, but difficulties in handling the great bulk of harvested crop have prevented the system from being accepted on commercial farms. However, a whole crop harvester has been developed at Silsoe in response to demand from farmers in the developing world (Metianu et al, 1990) and there may be significant further developments.

Header-stripper

3.3 A system of harvesting with an entirely different aim - the collection of grain only from the ears of the cereal crop - was once quite widely used in Australia and Argentina. Largely through work at Silsoe, this system was brought up to date for UK conditions. The 'header-stripper', unlike the whole crop harvester, has been taken up by a considerable number of British commercial farmers. The management of the standing straw left behind by the stripper poses problems but these are not insurmountable (Rush, 1990).

3.4 There has been considerable overseas interest in the 'header-stripper' system, notably in Czechoslovakia (Blahovec, 1988). A number of machines of British design are now working on the continent and in North America, as well as in the United Kingdom.

Combine speeds

3.5 Attention has been given in recent years to the effect on combine speed and capacity of the quantity of straw which goes through the harvester. Work in Sweden (Lundin and Ekstrom, 1985) showed how the weight of harvested straw is related to stubble height. These workers have also shown how the grain capacity of a combine, in tonnes per hour, increases as stubble length increases. The same Swedish paper gives a breakdown of the times taken for various harvesting-transport-storage operations, and their cost, on a large number of farms.

3.6 These Swedish workers point out that straw left in a very long stubble will normally dry out more slowly than if it is cut and swathed and they consider the economic implications of harvesting with a very long stubble in a situation where the straw is also required.

3.7 There has also been work in Scotland on the effect of straw yield variations on combine speed (McGechan, 1985).

Baling, compaction and handling

3.8 The costs of baling and handling straw have been the subject of discussion and depend very much on systems used. A summary is given in a MAFF publication (MAFF, 1984). Swedish work has concentrated on the time taken in the different steps of baling, stacking, storage and transport of Hesston bales (Pettersson, 1985).

3.9 Current methods of handling straw in the UK have recently been summarised (Neale, 1990) and methods used by a large-scale contractor and distributor and designed with industrial use in mind have also been described (Johnson and Hutchinson, 1990).

3.10 For some years there has been great interest in the compaction of straw to high density, either in the field or as a subsequent process. There have been several investigations of the fundamental aspects of the problem. Work reported in Canada has clarified the relationship between pressure and density when compacting different types of cereal straw (Ferrero et al, 1991).

3.11 The ideal way to achieve high density would be through a field machine of high capacity and acceptable size and power requirement. Attempts to produce such a machine for straw in the United States have not so far been successful. A considerable effort has been made in the United Kingdom to design an in-field straw wafering machine and a Department of Energy report has been issued (ETSU, 1991); however, a commercially viable field wafering or cubing machine is not yet in sight.

Fractionation

3.12 There has been increased interest in the fractionation of straw since it has become clear that certain fractions, e.g. chaff and leaf, have characteristics that make them more suitable for some uses than other fractions such as nodes and internodes (Audsley, 1988).

3.13 There is a wide range of fractionisation techniques. One of the simplest is the combing of wheat straw which separates leaf and loose material and leaves straight straw, mainly internodes, which are best for thatching.

3.14 Some separation of cavings and chaff occurs in the combine harvester and arrangements have been made in Canada to collect this light fraction for animal feed. There has been considerable recent research on aspects of straw chopping and fractionisation (O'Dogherty and Gilbertson, 1988; O'Dogherty and Gale, 1991; Gorial and O'Callaghan, 1990 and 1991; Smith and Stroshine, 1985). This work has focussed on the density of chopped straw and maize harvest residues, the aerodynamic behaviour of straw materials and the separation of fractions in a vertical air stream. Current work at the Silsoe Research Institute is concerned with the preparation of straw for industrial purposes, including devlopment of a straw slicer with low power requirement (Anon, 1983).

4. STRAW IN RELATION TO THE SOIL AND GROWING CROPS

Maintenance of soil organic matter

4.1 The Home-Grown Cereals Authority Research Review No. 11 deals with the incorporation of straw in the soil. This present review is confined to a consideration of related aspects such as mulching, composting and use as a growing medium, which were not listed in the previous Review No. 11. However, before reviewing these aspects, it is pertinent to consider whether straw incorporation materially affects long-term soil organic matter levels and whether this should be taken into account when considering removal of straw from farms.

4.2 The effect of ploughing in straw on the percentage of organic matter in the soil has generally been considered to be slight and very gradual. Experiments at MAFF Experimental Husbandry Farms between 1951 and 1968 (Short, 1974) confirmed that view.

4.3 In France (ITCF:APRIA, 1976) it was considered that incorporation of stubble and roots of cereal crops was sufficient to maintain organic matter levels. This conclusion is supported by recent Canadian work (Campbell et al, 1991) which showed that soil organic carbon was not depleted by straw removal. These Canadian workers hypothesised that carbon from the crop roots 'contributed more to the maintenance of soil organic matter than does straw'.

4.4 Published work on straw incorporation appears to support the view that there is no reason to refrain from removing straw from the field out of fear that such removal will lead to depletion of soil organic matter.

Use as a mulch

4.5 The word mulch is employed here to cover a wide variety of uses of straw on or near the surface of soils, for purposes of erosion control, moisture and temperature regulation, and weed, disease and insect control, as well as other related purposes.

Erosion control

4.6 In some American soils it has proved necessary to leave straw either on the surface or loosely incorporated in a shallow surface layer in order to combat erosion (Koelsch et al, 1977).

4.7 Straw as an erosion control mulch has been studied at the University of California Agricultural Experiment Station (Kay, 1983). A variety of methods of applying and holding down the straw are possible, including the use of blowers, netting (Plate 1), tackifiers, crimpicks and discing, depending upon the site to be protected. There are many references in the scientific journals to the value of straw mulches in erosion control and moisture retention (Losirikil et al, 1989; El Swaify et al, 1985; Kay, 1983).

4.8 A special method of using straw to retard soil erosion has been developed in the Pacific North-West of the United States (Hyde et al, 1984). The method is known as slot mulching and involves cutting slots approximately on the contour of sloping land and filling them with crop residues such as straw.

4.9 The inter-row planting of straw to prevent wind erosion of soils liable to blowing has become standard practice in some areas of eastern England and machines have been developed to plant several rows at a time (Macleod and Rickard, 1985).

Soil moisture and temperature control

4.10 Soil moisture and temperature control are particularly important in hot, dry regions. In Northwest India trials with un-irrigated wheat showed that straw mulch increased the yield of grain by 23.9 per cent and of straw by 23.1 per cent (Giri et al, 1983). Again in northern India, trials over a 4-year period showed that rice straw mulching at 6 tonnes per ha increased the yield of potatoes (Solanum tuberosum) and increased irrigation-use efficiency considerably (Singh et al, 1988).

4.11 In Georgia, USA, straw mulch was compared with plastic in tomatoes grown with micro-irrigation (Tindall et al, 1991). The straw mulch resulted in significantly greater infiltration rate and lower pH, bulk density, surface evaporation, cone index, soil temperature and matric potential than the plastic mulch; and these research workers concluded that straw mulches have the potential to improve tomato yields in high temperature environments, provided soil pH is controlled.

4.12 In recent years there has been a marked expansion of cultivation of Solanum tuberosum in countries with a hot climate and the use of mulches in these circumstances has been investigated in the Philippines (Taja and Zaag, 1991). They found that straw mulching together with optimal inorganic fertiliser or simply nitrogen at 50kg per ha substantially improved potato yields.

4.13 A comprehensive report (Miles, 1984) describes tests on the effect of straw mulches on blueberries, wine grapes, roadbanks and Christmas trees.

4.14 In the United Kingdom there have been few reports in scientific journals of the use of mulches in horticulture, but a fairly recent report (MAFF, 1984) states that 'widespread use of herbicides for weed control in fruit plantations has led to an increasing use of straw mulches to gain maximum benefit of the available soil water'. It is especially useful in helping to establish young fruit plantations, particularly where there are no facilities to irrigate the crop. This MAFF report estimated that 25-30,000 tonnes per annum of straw were used in England and Wales as mulch for top fruit

(Plate 2) and 10-12,000 tonnes for soft fruit crops.

4.15 The use of straw mulch in mature apple orchards in Kent has recently been described (Lovelidge, 1992). Here the straw is mechanically spread on unirrigated land to conserve moisture and reduce herbicide use and has given promising results over a number of years, including improved fruit size.

4.16 Layers of straw have been used, often in conjunction with plastic sheets, to enable root crops - particularly carrots - to be stored over winter in the soil in which they grow (Plate 3). Research on this system has been carried out at the Arthur Rickwood Experimental Husbandry Farm (Rickard, 1991). The possible use of straw covering to protect celery for Christmas sale has also been investigated at the Arthur Rickwood Farm (Jones, 1983).

4.17 Another way of using straw for temperature control has been reported from New Zealand (Pyke et al, 1988). These workers found that wraps made from materials such as straw prevented severe temperature fluctuations in the trunks of Kiwifruit trees during severe weather. These thermal insulation wraps may become more widely used.

Use on strawberries

4.18 The use of straw under strawberry plants, primarily to protect the developing fruit, is traditional and well-known. Less well-known is its use as a winter application to influence yield and ripening. (Pritts et al, 1989). A few hundred tonnes have been used annually in the United Kingdom in this way to retard flowering and fruiting of strawberries in their last cropping year (Plate 4).

Disposal of mulching straw

4.19 The disposal of straw used for short-term covering of carrots, strawberries and other crops presents a problem when burning is banned. Methods such as chopping and incorporation have been investigated at Experimental Farms (Runham and Cope, 1992).

Effects on following crops and weeds

4.20 In the United States there has been increased interest in 'conservation tillage', which often implies reduced cultivations and the incorporation of straw in the surface layers of the soil. This has focussed some attention on the allelopathic properties of the straw (Hicks et al, 1989). Wheat straw residues have been shown to have a negative effect on the establishment of a following cotton crop. Other United States work (Herrin et al, 1986) investigated the effects of wheat straw residues on the soya bean crop, but field evaluations 'were not highly correlated with greenhouse results'.

4.21 There are many references in scientific journals to the phytotoxic (plant-killing) properties of cereal straw. An important trial was recently carried out in eastern Quebec province on the effect of mulches of wheat, barley and oat straw in forest plantations (Jobidon et al, 1989). This work suggests that such mulches can give a valuable reduction in competing vegetation, possibly through the action of phenolic acids produced from the straw. The published papers make no attempt at cost/benefit analysis, and suggest that further trials should be carried out. There are indications from this Canadian work that straw mulching could be profitable in UK afforestation.

4.22 Earlier long-term trials of straw mulching in pine plantations in British Columbia (Weetman and Fournier, 1984) showed that 'a sustained increase in tree growth' resulted from the treatment. These researchers discuss the reasons for this. In spite of the high C:N ratio of the applied straw, the leaves of the mulched trees showed higher nitrogen than unmulched trees and it is suggested that decomposed C in the mulch led to increased microbial activity and N mineralisation. Elimination of weeds by the mulch may also have benefitted the growth.

4.23 Some striking results have been reported from Maryland, USA (Creager, 1989) from weed control trials over a 5-year period on rhubarb. In these trials straw-mulched plots produced larger plants, gave higher yields and had fewer weeds than all other treatments during the 5-year period.

4.24 The allelopathic action of straw in relation to cherry trees in Michigan has also been described (Putnam and Chung-Shih Tang, 1986).

4.25 There has been some investigation of the chemistry of the phytotoxic effects of wheat straw residues on certain weeds (Liebl and Worsham, 1983). These workers conclude that 'ferulic acid and other compounds (derived from the straw) may indeed play a role in reducing the growth of certain weeds in no-tillage cropping systems'.

Control of insects

4.26 The use of oat straw to control Macrosteles fascifrons, a vector of aster yellows in carrots, was tested in field trials in Minnesota (Setiewan and Ragsdale, 1987) and the mulch was found to give as good a control as a conventional insect spray programme. These workers suggest that it was the reflected light from the mulch that kept the insects off the crop.

4.27 Another example of the use of straw mulch to control an insect pest has been described in Virginia (Zehnder and Hough-Goldstein, 1990). Trials in 1988 and 1989 showed that a wheat straw mulch gave useful control of colorado beetle. In these trials straw mulch plus 2 insecticde sprays gave as good control as 6 insecticide sprays, and it was thought that straw mulching could be considered as a commercial option. The straw mulch had the effect of reducing or delaying oviposition by overwintering beetles and 'egg mass density was significantly lower on mulched plots'.

4.28 A rice straw mulch was shown in Philippine trials to suppress some insect pests in a following legume crop (Litsinger, 1982), apparently because increased light reflection from the straw had the effect of keeping aphids and froghoppers away from the crop.

4.29 The use of a straw 'mulch' under apple trees to encourage an earwig population on the trees which then controls aphids, may at first sight seem far-fetched (Carroll and Hoyt, 1984). However, these research workers in the apple-growing state of Washington, USA, found that the earwigs gave a good biological control of aphis, including woolly aphis, and the ground shelter provided by the straw apparently played its part. This piece of research work at least illustrates the complexity of interactions that occur when using a material such as straw in association with plant and animal life.

Control of diseases

4.30 Work in the United States has shown that a straw ground cover can have an important effect in reducing splash dispersal of *Colletotrichum acutatum* (Yang et al, 1990).

4.31 As a result of trials in the state of Victoria, Australia, research workers (Kollmorgen et al, 1987) came to the slightly surprising conclusion that a 'stubble mulch of 4 tonnes per ha of straw, buried at 5 or 10 cm reduced survival of take-all fungus in wheat crowns' and that 'it may be possible to reduce carryover of *Gaeumannomyces graminis* var. *tritici* inoculum with stubble mulches'.

4.32 The complexity of relationships between straw and, for instance, fungi, is illustrated by some Canadian work which showed that sterols contained in cereal straw may stimulate the production of spore-forming bodies by fungi such as Phytophthora in the soil and thus help to ensure the survival of such fungi in the soil (Thomson et al, 1986).

4.33 Another interesting effect of straw on plant disease has been shown in experiments comparing rockwool and straw as the growing medium for cucumbers (O'Neill, 1991). This work has shown that the silicon in straw, when taken up by the plant, significantly reduces damage from fungi such as Botrytis cinerea. ADAS trials of growing cucumbers on blocks of straw are continuing at Kirton.

4.34 There may be a special value in the use of straw mulches for leguminous crops (Mohan and Ali, 1969; Terada, 1971). Indian work (Sekhon and Kaul, 1984) has shown that Rhizobium innoculation of soya beans may be more effective if used in conjunction with straw mulch, leading to enhanced nitrogen fixation and greatly increased crop yield in some circumstances.

Influence on effectiveness of herbicides

4.35 The effect of the ash from field-burned straw on herbicide efficiency has been reported at some length. Less is known about the effect on herbicides of a straw mulch or of straw mixed into surface layers of the soil. Interesting American work (Dao, 1991) shows that such straw 'can be a temporary storage medium for herbicides, altering patterns of chemical dispersion in conservation tillage....' and 'there is the added benefit of continued slow-release and increased efficiency of these herbicides leading to a potential reduction in post emergence chemical inputs ..... as gradual desorption from the straw mulch may provide extended control of second flushes of weed emergence and growth'.

Fungitoxicity of smoke from straw

4.36 A side-issue of straw burning - the fungitoxicity of smoke - has been considered by American workers (Zagory and Parmeter, 1984). In greenhouse experiments they tested the effect of smoke from burned straw on various fungi but came to the conclusion that phytotoxicity from high smoke dosages caused more damage than did infectious diseases. However, these workers add that, '...home or farm production and the use of smoke condensates for inexpensive control of some plant diseases appears feasible and merits evaluation'.

Straw for composting

4.37 In recent years there has been increased interest in composting a wide range of waste materials. This has been due largely to the difficulty of disposing of such wastes, as land-fill and dumping in rivers and the sea have become more expensive or have been banned. The subject has been extensively researched (Gasser, 1985; Bertoldi et al, 1987).

4.38 In the UK, straw used for horse bedding has traditionally been used for mushroom compost. The great post-war increase in mushroom production led to the demand for compost outstripping supplies of horse bedding and most of the compost used today is made from straw to which other manure is added. Between two and three hundred thousand tonnes are used annually in the UK in this way (Flegg, 1985; Barrett, 1990; Wood and Smith, 1987).

4.39 The disposal of sewage sludge has become a problem in many countries and straw has proved a useful material to compost with liquid sludge (Border et al, 1988; Border, 1990).

4.40 In the United States, sawdust has been extensively used to compost with sewage sludge but straw has been found to be an excellent alternative bulking agent. Detailed trials in California have shown that straw has the advantage of quicker fermentation and that, 'in fuller scale operation the productivity of straw windrows would exceed the productivity of sawdust windrows by over 25%' (Hay et al, 1988).

4.41 There has also been considerable research in the UK on composting straw with dehydrated sewage sludge (Smith, 1990) (Plate 5).

4.42 Workers at Birmingham University have been researching composting processes for some years and have found that straw is a good bulking agent for use with a number of organic wastes, including vegetable and animal wastes (Biddlestone et al, 1990).

4.43 In France, straw waste from the maize crop has been successfully and commercially composted for some years with abattoir waste (Fromm, 1990).

4.44 The possibility that the availability of the phosphate in rock phosphate may be improved if it is mixed with composting straw, while at the same time it may speed up the composting process, has been investigated; the results of laboratory-scale tests, recently reported, appear promising (Singh and Amberger, 1990).

4.45 With increasing environmentalist opposition to the use of peat, there has been interest in the possible use of straw-based composts as a substitute. The arguments for and against such substitution have recently been summarised (Bragg et al, 1990). Straw-based peat substitutes are now being produced commercially in the UK (Edmonds, 1992).

4.46 The management and storage of compost has considerable influence on nitrogen losses. Losses from ammonia volatilisation can be serious in the making process and these losses may continue during storage/maturation (Witter and Lopez-Real, 1988).

4.47 Composting, by whatever method, requires labour and machinery; and at the end of the process the compost has to be saleable at a

price which will make the procedure less expensive and more acceptable than alternative methods of waste disposal.
Comparatively few trials have been reported on the value of compost to farmers and growers, but some have recently been reported from the UK (Staniforth and Smith, 1991). These trials indicate that suitably produced compost may have sufficient value to farmers and growers to make its production an attractive alternative to other methods of sewage sludge disposal.

5. USE OF THE FIBRE IN STRAW

Bale buildings

5.1 Baled straw has been used to make buildings for cattle, pigs and poultry and for the storage of crops such as potatoes. The insulation value of a typical bale with moisture content below 15 per cent makes it possible to achieve high wall insulation values of RSI-5+ (Bainbridge, 1986).

5.2 Straw bales have been used in the United Kingdom for poultry housing (Jones, 1959) but less commonly since the industry became concentrated in large enterprises.

5.3 Experiments are currently being carried out in Denmark with pig houses constructed of big bales with a tent roof (Danish Ministry of Agriculture, 1992) (Plate 6). The results of these trials with breeding sows at Bygholm will be awaited with interest.

5.4 Bales have been used in North America to make durable buildings, being stuccoed or plastered inside and out (Argue, 1980) (Plate 7).

Thermal insulation

5.5 Straw in a loose layer, or held in a type of quilt with netting or plastic sheet, has been used for insulation in, for instance, wagons transporting potatoes in winter, or to cover freshly laid concrete in frosty weather (Staniforth, 1979). The thermal properties of a straw layer have been compared with those of other insulating materials, with special reference to the soil (Pritts et al, 1989).

Cob and earth-straw mixtures

5.6 A great deal of development work on the use of mixtures of straw and earth in varying proportions has been carried out in recent years by the Craterre organisation near Lyons, where a number of experimental houses have been built (Anon, 1987[a]; Anon, 1985[a]).

5.7 Straw-earth mixtures have also been studied extensively in northern France, both for livestock buildings (Anon, 1987[b]) and for domestic buildings. It is possible to see a number of recently constructed buildings of this type in Normandy and, with the present emphasis on energy conservation, the technique may yet return, at least experimentally, to the UK.

5.8 In the United Kingdom a mixture of earth and straw, known as cob, was extensively used for house building in past centuries (Harrison, 1984), but the last such houses were built at Amesbury in 1919 (Williams-Ellis and Eastwick-Field, 1947).

Strawcrete

5.9 Strawcrete - a mixture of chopped straw and concrete - has been made in Essex (Staniforth, 1979; Godfrey, 1974). Experimental work continues in Germany on the use of unfired straw-clay bricks (Kratz, 1989). Vegetable fibres can be used to reinforce cement sheets (Lewis, 1979; Sinha et al, 1975) but, in the United Kingdom, the possibility of replacing asbestos with straw fibre has not been pursued.

Board, panels and mouldings

5.10 Compressed straw panels, known as Stramit board, have been manufactured in Suffolk for over 40 years (Mosesson, 1979) and a number of Stramit board factories are now operating in overseas countries.

5.11 The use of straw in bales or compressed board or as an insulating layer has been researched in Germany (Englert, 1980). Other experiments in Germany have tested different proportions of straw and wood flakes in particle board (Tröger and Pinke, 1988).

5.12 A system of particle board manufacture has been developed in the United Kingdom over the past 15 years (Barnes, 1987). Many difficulties have had to be overcome but the 'Compak' system which has been developed at Gainsborough has reached the stage at which several presses have been exported to Scandinavia and other overseas countries.

5.13 The cost of the binder has always been an important factor in the economics of straw particle board. An interesting development has been the use of cardanol, a byproduct of cashew nut shells as a binder with water-cooked rice straw pulp (Chawla and Negi, 1983).

5.14 At least one process has been developed in which finely ground straw is compressed and moulded (Harmer, 1988). A mixture of ground straw, synthetic resin or plastic material acting as binder and a very small amount of non-vegetable fillers, colourants and the like is partially compressed in a feed auger to about a quarter of its initial volume and then introduced into a press-mould in which it is pressed to about a fifth of its volume on entering the press mould. This process has not yet been commercialised.

Cardboard and paper

5.15 The potential for straw as a raw material for pulping has recently been summarised in a report which shows the trend in consumption of paper and board over recent years in a selection of countries (O'Brien, 1990). These trends are inexorably upward; in the UK consumption rose from 7.3m tonnes in 1980 to 10.12m tonnes in 1988. There are strong arguments in favour of increasing the use of straw for pulping.

5.16 There are examples, world-wide, of the use of straw for pulping for paper. In 19 countries in Europe and around the Mediterranean there were some 48 pulp mills using straw (Truman, 1974), but many of these have ceased production and it is mainly the larger and more efficient units that remain.

5.17 There is extensive literature on the use of cereal straw for paper, including the use of rice straw for this purpose. This review is concerned mainly with up-to-date references to the pulping of cereal straw in Europe, but including some overseas papers which have relevance to UK circumstances.

5.18 An ambitious plan for the production of high grade paper at a completely new plant on Humberside, using straw from the east of England, has been publicised. The aim was to use around 500,000 tonnes of straw per annum (Brown et al, 1990). This plan has not yet been put into action.

5.19 Another smaller project to produce unbleached pulp for use in the production of packaging material is being carried out by the St. Regis Paper Co. in South Wales. The objective is to test methods of using a proportion of pulp produced from straw in a mixture suitable for packaging papers. The machinery is now in place and the trial will start shortly, using a few hundred tonnes of straw. The aim is to use a few tens of thousands of tonnes of straw at the South Wales site and then at other mills in the UK.

5.20 The production of unbleached pulp from straw continues at other European sites, notably in Spain (Balet, 1982). The Spanish SAICA mill is producing around 100,000 tonnes of straw pulp per annum employing an anaerobic-aerobic system of effluent treatment (Velasco and Sarner, 1986).

5.21 An Australian plan to install a SAICA-type 100,000 tonnes per annum pulp mill in Western Australia, north of Perth, has obtained government backing. It is planned to produce pulp from straw which will be significantly cheaper than wood pulp (Anon, 1990).

Dissolving pulps, rayon

5.22 It has been known for many years that the cellulose in straw can be rendered viscous and extruded to form an artificial fibre - usually known as rayon (Rydholm, 1965). Softwood pulps have been used for this purpose in recent years but there is some continuing research work into the use of cereal straw for the production of these 'dissolving pulps'. Egyptian researchers (Abou-State et al, 1986; Abou-State, 1987) have suggested a method of obtaining from wheat straw a viscose pulp which has advantages over similar commercial softwood pulp.

Fractionation for pulping

5.23 The importance of using specific fractions of straw for pulping for paper has been mentioned in recent articles In the Dunaujvarosi mill in Hungary a 10% light fraction is separated and made into briquettes for fuel (Plate 8) leaving a 90% fraction better suited for pulping (Szekeres and Kochegarova, 1990) . In Taiwan it has been found that a 70% fraction of rice straw consisting mainly of internodes and sheaths can be separated out by winnowing to give a better pulp yield and strength than the remaining 30% fraction (Chiou, 1990).

5.24 There are many references in the databanks to technical aspects of straw pulping including a variety of pulping methods and to methods of dealing with silica and chemical residues. These all have a bearing on the future use of straw in paper making, but will not be detailed here.

Pulping mustard straw

5.25 Although strictly outside the scope of this review, it is of interest to note Indian work on pulping mustard straw (Karira and Dhawan, 1989). The short fibred pulp yields were comparable with those from wheat, though the strength properties were lower. The inference is that oilseed rape straw may also be worth considering as a raw material for semi-chemical pulping.

6. STRAW FOR FUEL

Calorific value

6.1 The characteristics of straw as a source of energy are well understood. (Strehler, 1980; Staniforth, 1982; Hare, 1987). The calorific value varies with moisture content and one set of determinations is as shown in the following table.

CALORIFIC VALUE IN RELATION TO MOISTURE CONTENT

Moisture content	Calorific value of straw	
(%)	(kJ/kg)	(kcal/kg)
10	15100	3600
12	14700	3500
14	14300	3400
16	13700	3310
18	13500	3215
20	13100	3120
25	12100	2880
30	11000	2620

Source: Strehler, 1980.

6.2 The energy value of straw is approximately the same as that of wood at similar moisture content, and about half that of good coal and rather more than one third that of fuel oil. Straw is generally more bulky and expensive to handle than wood which is at a similar disadvantage to coal. Fuel oil is much the most convenient of these fuels to use but gas is generally even more convenient.

Combustion systems

6.3 Nothing can be done to alter the inherent energy values of these fuels and, therefore, their relative price will determine their competitiveness, always having regard to factors such as reliability of supply and the efficiency and convenience of their use.

6.4 Most of the research and development on straw as a fuel in recent years has been devoted to improving the efficiency and convenience aspects.

6.5 A number of publications have summarised the main aspects of straw use as a fuel (Balls, 1980; MAFF, 1984; Staniforth, 1982; Eckhoff, 1977; Requillart, 1983; Beagle, 1978; Stewart et al, 1979; MAFF, 1980).

Small-scale burners

6.6 In the United Kingdom it has been calculated (MAFF, 1984) that rather less than 200,000 tonnes per annum of straw are used on or near straw-producing farms for domestic heating and hot water and for a variety of purposes such as the heating of glasshouses (MAFF, 1983), offices, livestock accommodation, swimming pools and the like. In Denmark many thousands of straw burners have been installed on farms.

6.7 The efficiency of the comparatively small (<300KW) straw burning boiler has been improved greatly since the early models were introduced (Teisen, 1987). Thermal efficiencies of up to 65 per cent are now possible, with very low emissions. Water heat accumulators are incorporated and the burners are such that cleaning out is done weekly or even fortnightly. Fully automated stoking systems have not proved to be practicable and economic on these small systems. However, it is usually now sufficient to stoke them once or twice a day (Teisen, 1990).

Large-scale burners including 'district heating'

6.8 In France there have been few domestic straw-fuelled systems but a considerable number of maize- and grass-drying plants have used straw, particularly when oil prices were high (Requillart, 1983).

6.9 Two examples of large straw burners in the United Kingdom have been reported upon by ETSU - the Energy Technology Support Unit at Harwell (ETSU, 1988 and 1989). These are respectively, projects for using straw as fuel to dry chalk at Needham Chalks Ltd. and for supplying hot water at Woburn Abbey.

6.10 A large Austrian farmers' cooperative annually cooks 36,000 tonnes of potatoes, using some 3,000 tonnes of straw as fuel, to produce about 60 per cent of the country's French fried chips (Staniforth, 1991; Anon, 1985). The factory, near Vienna, has been operating successfully for ten years (Plate 9).

6.11 Very large, whole-bale burning furnaces have recently come into use which incorporate fully automated stoking systems. The development of these systems has been most widespread in Denmark. The social and economic background as well as the technical design of these systems, which have been used mainly for 'district heating', have been described (Iversen, 1984).

6.12 These large burners have outputs usually between 0.25 and 25MW - some larger ones also generate electricity. A few of the large straw-fuelled 'district heating' systems have been installed in other European countries. One at Villeparisis, a suburb of Paris, heats 250 municipal flats.

6.13 A feature of the Danish and French district heating burners is that they are stoked automatically with Hesston big square bales using overhead grabs activated by signals from the burners. The installations are expensive, requiring far more space than, for instance, the natural gas burners which supply most of the central heating in Villeparisis. The Danish systems are economic at present only because there are in that country heavy taxes on energy derived from fossil fuels. They are also feasible in Denmark because they can take over from existing district heating systems that previously used other fuels.

The fluidised bed system

6.14 The fluidised bed system of combustion has been tested in several countries, including the United States (Kansas State University Centre for Energy Studies, 1977) and the United Kingdom (Washbourne and Wilton, 1988). The latter workers concede that simple big bale burners have considerable advantages but say that the 'fluidised bed unit should not be ruled out'. Spanish workers (Bilbao et al, 1988) have studied techniques for mixing straw and sand in fluidised bed combustion. They point out that sand tends to settle at the bottom of the bed while the straw rises to the top and they propose a model for mixtures to be used in fluidised bed systems.

Other stoking systems

6.15 Other methods of overcoming the problem of automating the stoking of straw have included milling the straw to a fine dust and feeding pneumatically (Miles, 1976; Lasseran, 1980); chopping and feeding by auger or ram (Strehler, 1980); cubing or briquetting. The disadvantage of these mechanical treatments is that they themselves consume considerable energy and add so much to the cost of the fuel (Anon, 1991[b]) that the straw will often no longer compete economically with other fuels.

Briquetting

6.16 There may, however, be circumstances such as apply at the paper mill at Dunaujvaros, Hungary. Here, as mentioned above, a fraction of the straw is briquetted for sale as fuel where it is said to be fully competitive with the local, poor-quality brown coal. In France, straw has been pelleted for many years as an out-of-season activity at lucerne drying plants and sold for use in domestic boilers. In the United Kingdom a few straw briquetting presses remain in use on farms, converting surplus straw and utilising labour in autumn and winter, to supply local households where the briquettes are often used as a wood substitute along with coal. A combination of wood and straw pellets burns well and reduces slagging problems (Miles Jnr, 1985).

6.17 A careful analysis of the economics of straw briquetting for energy production has been made for German conditions (Kolloch et al, 1987). They compare straw briquettes with wood, oil and coal in automatically and manually stoked burners and assume the briquetting plant working at around one tonne per hour output for 1500 hours of operation per annum. They give briquetting costs of between DM75 and DM190 per tonne and conclude that in competition with oil 'one cannot expect a long term market for straw briquettes'.

6.18 Other detailed studies of the power requirement for briquetting wheat straw have been carried out in Germany (Strehler and Stützle, 1987; Apfelbeck et al, 1990). Using different types of press, these workers concluded that comminution of the straw (with Cormall chopper) and briquetting required some 5 to 7 per cent of the energy content of the straw. In the same trials, rape straw required 4 to 5 per cent of its energy for chopping and briquetting to dense, durable briquettes. The throughput of the press varied according to the material - 0.62 t/h for wheat straw, 0.77 t/h for rape straw and 0.92 t/h for whole crop wheat.

6.19 Techniques and economics of briquetting straw for fuel have been investigated at the Technical Research Centre of Finland (Wilen et al, 1987). This interesting work includes consideration of straw quality with particular reference to ash fusion temperatures and the use of portable pelletising units. The general conclusion arrived at is that 'straw pellets are, in certain cases, competitive with fuel oil.'

Emissions

6.20 The matter of possible harmful emissions in the smoke from straw-burners, and in particular the possible emission of dioxins, has been considered in Denmark (Nielsen and Blinksbjerg, 1989). Their research compared emissions from burners using straw, oil, coal and coal with straw. Their provisional conclusions are that, 'dioxin emissions are low in comparison with those obtained from the incineration of municipal solid waste. The results indicated 'a dependence between combustion quality and dioxin emission, but this could not be enlarged upon owing to the low number of samples taken ...'.

Oil and gas production by digestion

6.21 Oil or gas production by digestion and a number of techniques for doing this are considered in the section on biological treament of straw.

6.22 Another way of converting the energy in straw to a more convenient form would be to convert it to ethanol.

6.23 Methane (biogas) production from straw has been carried out experimentally, and to a limited extent commercially, for many years (Anon, 1976). It is now of some interest as a combined operation in conjunction with the breakdown of animal slurries (Llabrés-Luengo and Mata-Alvarez, 1987).

6.24 Studies in Kansas (Handa et al, 1977) considered these possibilities in some detail. They concluded that the process was not economic at current costs for natural gas but they add that, 'Additional points of consideration would be benefits attained from energy self-sufficiency and the reduction of the environmental damage caused by feed-lot run-off'.

Pyrolysis

6.25 Pyrolysis is a method by which the energy in straw could be converted into a gaseous form. The process has been known and researched for many years and a number of variations of the basic process are well understood. Current economic prospects have been summed up in the United States (Anon, 1991[b]) - these 'systems will .... depend on high fuel costs to encourage developments in the future'.

6.26 There have been interesting developments of mobile straw pyrolysers designed mainly for use in developing countries (Esnouf et al, 1987). This equipment is designed to work at 400-500°C and can be transported from village to village by lorry.

6.27 A system for pyrolysing biomass, including straw, has been developed in Canada which has given promising economic results (Scott and Piskorz, 1985). This is a fluidised bed system at atmospheric pressure.

6.28 Indian workers (Teckchandani and Dubey, 1986) reported a pyrolytic process in which materials such as straw or municipal waste can be converted 'with little machinery' into pellets for fuel which burn 'with almost the same, or better, efficiency as charcoal ...'

Manoil

6.29 An entirely different process for converting straw to oil has been developed at the University of Manchester Institute of Science and Technology (McAuliffe, 1990). This process works at medium temperatures and pressures with the aid of a catalyst. A continuous rig, working at UMIST, has produced oil of high calorific value (14,000 Mj/tonne) and containing negligible sulphur and nitrogen. However, this also can become economic only if the price of straw is very low and/or the cost of oil is very high.

Electricity generation

6.30 Some years ago researchers at Kansas State University made a thorough investigation of the techniques and economics of straw as a fuel in a municipal electric power generating plant (Kansas State University Centre for Energy Studies, 1977).

6.31 There has recently been much interest in the possibility of using large quantities of biomass, including straw, to provide renewable energy for the generation of electricity. Shell UK Ventures Ltd has made a study of the various options. Another study has been carried out in the Punjab (Jenkins and Bhatnagar, 1991) to ascertain the feasibility of using large quanitities of surplus paddy straw, which are currently burned in the field, to generate power. This latter report concluded that the construction of a 40 MW station, fuelled by straw, 'should be considered as part of the larger economic and social system of India'. In Denmark at the present time several of the larger district heating installations are using straw to fuel electricity generating plant.

6.32 Analyses of the economics of various methods of utilising the energy in straw have generally tended to favour direct combustion. An Italian paper of 1984 sets out the comparisons (Pellizzi, 1984).

6.33 Some aspects of the conversion of straw to oil and gas are considered in the next chapter.

7. BIOLOGICAL TREATMENT OF STRAW

Organisms normally present in straw

7.1 Before going on to consider biological treatments for straw it is useful to emphasise that straw normally carries a considerable number of organisms. French workers (Pelhate and Agosin, 1985) identified about one hundred species that are commonly present on dry wheat straw at harvest in temperate zones. These remain latent on dry material but can become competitive and harmful if straw is dampened or 'modified biologically'.

Edible mushroom production

7.2 There are many reasons for biological treatments of straw. One is for the production of mushrooms and there is a very large literature on this subject, which will only be touched upon in this review. For the commonest commercially grown European mushroom (*Agaricus bisporus*) methods have been evolved for the production of 'synthetic' compost from straw (Gerrits, 1974). With the expanded market for this type of mushroom, the consumption of wheat straw to make compost has increased to around 300,000 tonnes per annum in the United Kingdom in recent years (MAFF, 1984). The oyster mushroom (*Pleurotus florida*) is also grown on straw (Kurzman, 1975). Although at present only produced on a small scale in the United Kingdom, there may be an increase in oyster mushroom production, as there has been in France (Plate 10).

7.3 Other reasons for treating straw biologically include improvement of straw as a feed, assistance in pulping for paper and board and the production of a variety of chemicals varying from biogas to sugar. In the past ten years there has been greatly increased interest in these biological treatments and many successors to basic texts (Burnett, 1978; Zadrazil, 1977; Stapleton, 1981; Stacey, 1976).

Biotechnology and pulping for paper

7.4 In this review it is impossible to cover in any detail the many applications of biotechnology to the paper industry in recent years. Over 100 papers or posters were presented at the 4th International Conference on Biotechnology in the Pulp and Paper Industry at Raleigh, North Carolina and Myrtle Beach, South Carolina May 16-19 1989. These deal almost exclusively with the treatment of the ligno-cellulose in wood, but similar treatment would often apply to straw pulping.

Upgrading feed value of straw

7.5 One of the main aims of those researching the biological treatment of straw has been to improve its feed value. Early work in the United Kingdom (Hartley et al, 1974) pointed to the possibility that the in-vivo digestibility of straw could be increased by biological means. In Hungary a feed called Mycofutter, was produced from straw by biological means nearly thirty years ago. (Heltay and Petofi, 1965). Work on the effect of fungi on straw has been continued much more recently (Calzada et al, 1987), using Pleurotus sajor-caju and in India (Gupta and Langar, 1988 and 1991) using Pleurotus florida on wheat straw. In other work in the Punjab (Bakshi and Langar, 1991), spent wheat straw compost, after mushroom production, was tested as feed for buffaloes. This work confirmed that the spent compost had high ash and lignin contents but a usefully improved percentage of crude protein when compared with wheat straw; it was suggested that spent straw compost mixed with wheat straw and cereal could 'meet the daily requirements of an adult ruminant'. Also at the Central American Research Institute for Industry, there have been tests of basidiomycetes on a mixture of wheat straw and coffee pulp (Calzada [a] et al, 1987). Species of Pleurotus, including P. ostreatus, the edible oyster mushroom, grew well on the mixture, but the feed value of the spent straw/coffee pulp mixture was lower than that of pure straw. In an Indian study (Kahlon and Dass, 1987), several cellulolytic, non-toxic fungi were tested as fermentation agents with a view to improving the feed value of rice straw. In yet another Indian study, urea-treated wheat straw was fermented with fungi (Kumar and Singh, 1990) under non-sterile conditions with the aim of improving its feed value.

7.6 Experiments have also been carried out in Ireland (Wilkinson et al, 1991) on the upgrading of wheat straw by fungal fermentation. A mutant strain of a basidiomycete fungus increased the crude protein value of alkali-treated wheat straw, but the particular strain tended to revert to the less-effective wild-type strain after about six months.

7.7 Other United Kingdom workers have been using enzymes produced from fungi to improve the digestibility of straw (Khazaal et al, 1990). Enzymes have also been tested in the UK for their hydrolytic effect on the polysaccharides of straw (McCrae et al, 1989). The Department of Microbiology at Liverpool University has reported work on the saccharification of straw by Actinomycete enzymes (Ball and McCarthy, 1988).

7.8 A fifty-page review of the enzymatic conversion of cellulosic materials covering developments between the end of World War II and 1984 has been prepared by a Russian consultant to UNIDO (Klyosov, 1986). This interesting review explains how these developments were triggered by huge losses in cotton gear suffered by United States forces in the South Pacific during World War II causing several laboratories to be set up to investigate the causes.

Biological action on soil-incorporated straw

7.9 A number of fungi isolated from straw in arable soils in the UK have been tested (Bowen and Harper, 1990) and have shown interesting variations in their ability to degrade lignin.

7.10 There have been attempts in India to speed the degradation of soil-incorporated straw by inoculating it with suitable organisms. Such trials have been reported on rice straw (Varma and Mathur, 1990). It has been suggested that similar inoculants could be used with incorporated straw in the UK and some commercial products have appeared on the market; however, there is little clear evidence of their practical value on the farm.

7.11 The potential value of microbial action on straw in the soil has been investigated in recent Australian work (Halsall and Goodchild, 1986). The possibility of using the energy released in the microbial breakdown of straw to fuel the fixation of atmospheric nitrogen has been under review for many years and these researchers have demonstrated that mixed populations of suitable bacteria can improve the efficiency of this process.

Pre-treatments for biological action

7.12 Much of the experimental work on the biological treatment of straw has been concerned with suitable pre-treatment.

7.13 Workers at Oregon State University investigated the effect of different grinding methods on the fermentability of straw (Han and Chen, 1978). They found that disc-refined or defibrized straw produced more sugars when fermented than hammer-milled straw and they attributed this to the fiercer action of the disc-refiner in removing the waxy surface of the straw as well as in separating fibre bundles.

7.14 Steam explosion has been used as a pretreatment of wheat straw, in conjunction with acid catalyzation for subsequent enzymic conversion to sugars (Excoffier et al, 1990) and fermentation to ethanol.

7.15 United States researchers (Grohmann et al, 1989) describe a technique for chemically attacking ester groups in straw cell walls in order to render the cellulose fraction more digestible in enzymatic hydrolysis.

7.16 Other work bearing upon the enzymatic saccharification of straw has been carried out in the United States (Gould[a], 1985) and in France (Katrib et al, 1988). This work demonstrates that pre-treatment of wheat straw by organic solvent greatly improves the enzymatic saccharification yield.

7.17 Japanese workers (Magara et al, 1989) found that pre-treatment of rice straw by microwave irradiation increased its susceptibility to enzymatic digestion and led to improved yields of ethanol. These workers say that the heavy requirement for electricity in this treatment may be mitigated by certain procedures.

7.18 Recent American research work has investigated alkaline hydrogen peroxide-treated wheat straw as a raw material for biological conversion by Ruminococcus species (Gould[b], 1985; Odenyo et al, 1991). This work was done with the primary aim of improving the nutritive value of the straw but it was suggested that these organisms could be used for saccharification of hydrogen peroxide-treated straw for the production of industrially important byproducts, including methane.

7.19 In Colorado in the United States it has been found that the best pre-treatment for wheat straw for solid fermentation with Chaetomium cellulolyticum was ammonia freeze explosion, followed by steam and alkali treatment (Abdullah et al, 1985). Other workers in Australia (Puri and Pearce, 1986) obtained good saccharification yields from wheat straw by subjecting it to alkali treatment followed by an explosive discharge through a defibrating nozzle. They attributed the improved yields from subsequent enzyme treatment to 'the efficacy of fiber separation and disintegration which increases the surface area and reduces the degree of polymerisation'.

7.20 In laboratory scale trials in Italy (Capretti et al, 1987) steam-explosion was found to improve greatly the susceptibility of straw to enzyme attack and this form of treatment was considered worthy of further experimentation in relation to the paper industry, animal feeding and chemical production.

Engineering for biological treatment

7.21 The engineering of enzymatic straw treatment has recently been studied (Gonzalez et al, 1989) with particular reference to enzyme recycling.

7.22 German workers (Borchert and Buchholz, 1987) have also experimented with machinery designs for enzymatic hydrolysis of cellulosic materials.

Fermentation for methane and ethanol

7.23 The production of biogas from straw has been studied for many years and results to 1980 were summarised by Staniforth, 1979. There has been some further work on this subject in the past few years in Oregon (Hashimoto, 1989) and in India (Dar and Tandon, 1987). The Oregon work emphasises the importance of the inoculum/substrate ratio in determining methane yield in small-batch fermentors. The Indian work shows that alkali-treated wheat straw added to cattle dung greatly increased biogas production.

7.24 Methane production from straw/manure mixtures has also been studied in Spain in recent years (Llabrés-Luengo and Mata-Alvarez, 1987). Other experiments to test the usefulness of alkali treatment of straw for anaerobic digestion of straw for methane production were carried out in the United States (Pavlostathis and Gossett, 1985). They found that such pre-treatment doubled the biodegradability of the straw but they nevertheless concluded that a 'cost analysis showed that, at the present price of natural gas, methane production from wheat straw is not currently attractive'.

7.25 During the past decade or so, nervousness about oil supplies has directed much research work to the possibilities of producing a substitute fuel such as ethanol from biomass such as straw.

7.26 Work in the Punjab describes the fermentation of wheat straw to ethanol (Kaur, 1989). In this work the straw was hydrolysed by sulphuric acid or by enzymes before being fermented by Pachysolen tannophilus to ethanol. Catalysts were also used in this work and satisfactory yields and fermentation efficiency were reported.

7.27 Ethanol production from straw has been researched at the Centre for Biotechnology at Imperial College, London (Amartey et al, 1987). These workers used a mutant bacillus to continuously ferment wheat straw previously hydrolysed with acid in an attempt to reduce production costs.

7.28 Polish work (Szczodrak, 1989) has shown that the use of cellulase produced by a mutant of Trichoderma reesei can improve the yield of ethanol from wheat straw. In a fermentation process employing this mutant, the yield of ethanol was increased to 3.4 per cent, weight for weight, and the reaction time shortened to 24 hours.

7.29 Recent French work describes the fermentation to ethanol of wheat straw by a strain of Pichia stipitis (Delgenes et al, 1990). In this case the straw was pretreated with sulphuric acid to convert the polysaccharides to sugars.

7.30 In Greece, pre-treated straw has been converted to ethanol by Fusarium oxysporum. Delignification of the straw by sodium hydroxide was found to affect markedly the conversion to ethanol (Christakopoulos et al, 1991). These research workers consider that the high yield of ethanol obtained justifies further work on this type of biological transformation.

Economics

7.31 The various biological (including enzymatic) treatments for straw are of great scientific interest but the straw producer is looking for economic outlets for his cereal byproduct. A few of the scientific papers that appear in the literature consider this aspect (Pavlostathis and Gossett, 1985; Zaachi et al, 1988). In the latter, Swedish workers have made an economic evaluation of enzymatic hydrolysis of phenol-pretreated wheat straw. They conclude their paper by saying that, 'Improved raw material utilisation, in terms of hemicellulose conversion and enzyme recovery appears to be necessary for the economic feasibility of the process'. Experienced Danish workers (Rexen et al, 1988) express doubts about the likelihood of an economic return from the hydrolysis of straw. They point to the relative cheapness of many starchy waste materials which can be more easily fermented. They also make the point that the price of cellulose fibres 'is more than double that of starch' and consider that the most economic way of using straw may be in the exploitation of its high fibre content, particularly when the whole straw can be efficiently fractionated. This point of view has also been set out by Staniforth, 1982.

7.32 The difficulty of controlling the action of biological agents (Burnett, 1978) remains and will always be there under non-sterile conditions. In this connection, work in the Punjab showed that, in some circumstances, cold water washing of straw improved the substrate sufficiently to allow satisfactory fermentation by <u>Coprinus</u> sp. (Gupta and Langar, 1991).

7.33 Although there are as yet few, if any, commercially important examples of the biological treatment of straw (apart from the well-established uses for mushroom production) it is considered important to keep those treatments under review. The examples cited above give an indication of which biological agents could assist in the pulping of straw for paper or in the production of fuel and other chemicals.

Biodeterioration and thatch

7.34 It is convenient also to mention in this chapter some studies carried out at Bath University on the biological degradation of straw (Kirby and Rayner, 1989). Cases have occurred of premature rotting of thatched roofs and it was thought that particular micro-organisms could be involved. However, no clear evidence of this has yet been discovered.

8. BEDDING FOR LIVESTOCK

Amounts used

8.1 Straw has traditionally been used as bedding for livestock but there has been little precise information on the total quantity used for that purpose.

8.2 A National Farmers Union Report (NFU, 1973) estimated that 36.4% of straw was used for bedding and crop storage. The amount so used was certainly reduced subsequent to that date as more and more livestock were housed intensively on concrete or on slats.

The slurry problem and straw absorbency

8.3 The management of slurries has become a serious environmental concern (MAFF, 1968; Baxter, 1989) and there have been a number of investigations into straw bedding as the alternative to concrete and slats in recent years.

8.4 There have been some fundamental investigations into the absorbency of various materials, some in connection with the reduction of silage effluent. At Reading University (Rowe et al, 1987) untreated winter and spring barley straw both absorbed around twice as much water as one thick-walled variety of wheat straw (Copain). Tub-grinding and chemical treatment did not improve absorbency. At the Silsoe Research Institute (Schofield, 1988) it was found that whole barley straw retained 20 per cent more water than did chopped barley straw. The Silsoe work indicated that 1kg of unchopped spring barley straw will absorb about 2.4 litres of water, and the ADAS Farm Waste Unit recommends that requirements for straw for bedding should be based on 1kg of straw absorbing 2.2 litres of urine. It is suggested that 'the hollow stems will be an important factor governing how much and how quickly water is taken up and held by straw'.

Animal and human welfare considerations

8.5 The stock requirement and economic implications have recently been summarised (Corning, 1990), and this paper also mentions the need to consider the welfare of stockmen which may be affected by dusty straw.

8.6 The nature of the dust problem is explained in a Scottish Agricultural College Centre for Rural Building publication (Robertson, 1989). Dust control measures are described in a variety of situations, including straw handling, and legal requirements are considered.

8.7 The potential hazard from exposure to spores arising from hay, grain and straw has also recently been investigated in Finland (Kotimaa, 1990). UK health aspects have been detailed at a recent conference (Stockton, 1990).

8.8 Experiments in Australia (Hutson, 1988) on the requirement of sows for straw for nest-building gave inconclusive results.

8.9 Different systems of bedding ponies have been compared in the United States. (Hunter and Houpt, 1989) The ponies preferences were determined by using video recordings of night time behaviour. They much preferred bedded to unbedded stalls but there were no clear preferences for straw as compared with wood shavings.

8.10 The use of straw bedding in relation to 'organic' livestock production systems has been considered in some details in a paper from the West of Scotland College (Parish, 1990). This paper points out that, 'The housing of cattle in buildings where the whole of the lying and loafing area is slatted, is prohibited' in organic production and goes on to consider how the use of bedding, such as straw, and the production of FYM may be introduced.

Health aspects

8.11 A number of workers have carried out trials with the aim of relating aspects of animal health to bedding systems. In Ohio (Hogan et al, 1989), rates of clinical mastitis were related to the use of organic (including straw) and inorganic bedding materials. In Germany trials have been reported (Brentano von et al, 1979) which relate the foot health of young cattle to the type of housing used. Here it was found that 'harder horn and lower water content in the claws of calves on slatted floors better protects the sole against traumatic injuries'.

8.12 In the United Kingdom, trials have been reported on the effect of vaccination against foot rot in young sheep wintered in straw yards. (Kerry and Craig, 1976). These workers found that an outbreak of footrot in the unvaccinated sheep was 'undoubtedly helped by the warm damp conditions underfoot'; however vaccination gave good protection.

8.13 A laboratory study in Minnesota of the effect of bedding material on the growth of mastitis pathogens compared five sterilised bedding materials - hardwood chips, recycled dried manure, chopped newspaper, softwood sawdust and chopped straw. (Zehner et al, 1986). The results of the tests are interesting, but the authors admit that they would not necessarily be reproduced under practical conditions in barns and they conclude that, 'high bacterial counts under barn conditions are influenced by factors more complex than type of bedding used.'

8.14 The possible ill-effects of straw bedding in stables has been a concern of horse keepers. Tests carried out with thoroughbred horses in Hong Kong (Mason et al, 1984) on the incidence of exercise-induced pulmonary haemorrhage, in which straw was compared with paper as bedding, concluded that no 'significant difference could be demonstrated in the incidence of EIPH resulting from the use of paper bedding in preference to straw'.

8.15 In an analysis of 391 farrowings over a 19 month period, carried out at Terrington Experimental Husbandry Farm, piglet mortality and treatment for scouring were lowest with straw-based bedding.

8.16 The influence of straw bedding on the incidence of tail-biting in pigs has been investigated in Scotland (Arey, 1991). It was shown in a case study that the provision of straw bedding was not sufficient to eradicate the problem completely, but it is concluded that the provision of such bedding should be among the first measures to take in order to control tail-biting.

8.17 In an observation study of two English dairy herds, in one of which there was a problem of lameness, it was found that increasing the amount of straw used in cubicle bedding in the problem herd prevented the incidence of further lameness problems (Colam-Ainsworth et al, 1989).

8.18 A study in North Wales with 40 spring calving cows (Schofield and Phillips, 1988) compared groups housed in straw yards and in cubicles, with and without prostaglandin injections. It was concluded that both straw yards and prostaglandin injections offer scope for improved reproductive performance, by improving conception rate and reducing the number of days to first service and the calving to conception interval.

8.19 Another health aspect of straw bedding - the encouragement of fly breeding - has been investigated at Beltsville in the United States. (Schmidtmann et al, 1989). Straw bedding was found to encourage fly breeding more than wood chips. These workers conclude that 'straw bedding promotes muscoid maggot growth' and they suggest that this growth may be partially controlled by feeding the livestock with cryomazine which is then delivered to the bedding via the animals' urine.

Labour requirements and economics

8.20 There has been some experimental work on systems for using straw as bedding which reduce the labour required while controlling the amount of straw used. At the Centre for Rural Building, Craibstone, Bucksburn, Aberdeen (Bruce, 1990) a system known as 'strawflow' has been developed for pigs. The amount of straw used in this system is much reduced but it has been shown in a mathematical model (Bruce, 1991) that the resulting dung can still be handled and stacked as a solid. This system is said to accord closely with current animal welfare codes.

8.21 It has been difficult to prove the benefit of straw litter, in terms of livestock output; experiments in Australia (Hutson, 1988) on the requirement of sows for straw for nest-building gave inconclusive results. In a later study at Terrington EHF (Edwards and Furniss, 1988) the effect of supplying straw in farrowing crates was compared with unstrawed crates. Results were inconclusive, partly, it was suggested because crates do not permit nest building. However, lack of straw in the crate appeared to increase sow restlessness and it was suggested that future trials with larger numbers of pigs are required.

8.22 The Orkney sloped floor (Robinson, 1984) was developed in an area where straw is not plentiful. It is claimed to be suitable for all types of cattle except dairy cows and the system is said to cost 35 per cent less than slatted courts.

8.23 Different horse bedding materials, including straw, were tested at the University of Kentucky from the points of view of labour requirement and dust and health (Taraba et al, 1987). Dust levels depended on the relative humidity of the atmosphere. Wood shavings and rice hulls required less labour, less storage space and less 'disposal space' than straw.

8.24 There has also been considerable interest in recent years in the use of straw for litter for poultry (Plate 11). In general, wood shavings have been preferred, but they tend to be expensive. Satisfactory systems have been worked out for using shredded straw which can cost 30 per cent less than shavings-based systems (Anon[a], 1991). These systems include extracting dust from the straw and treating it with fungicide.

8.25 The covered strawyard system of keeping egg-laying fowls, as an alternative to cages, was investigated in Scotland (Gibson et al, 1985). These workers concluded that it would be premature to make definite conclusions but they list a number of findings, including higher feed intakes by hens kept in strawyards.

9. STRAW FOR FEED

9.1 As stated in the introduction, the most important aspects of straw as a feedingstuff - those related to feed for ruminant animals - are dealt with in HGCA Research Review No. 24. This short section of the present review deals with straw as food for non-ruminants and also includes notes on some less well-known aspects of 'ensiling' straw with other products.

Horses

9.2 Straw and chaff have long been important in rations for horses. Traditional knowledge of this subject was summarised earlier in this century (Crowther, 1911). There are more recent references to straw as feed for horses in Europe (ITCF:APRIA, 1976) and in North America (Miles Jnr, 1978; Cuddeford, 1986.)

Rabbits

9.3 Straw can be an important element in the food of rabbits. There are a number of recent references to the use of straw, some dealing with alkali-treated straws (Lindeman et al, 1983; Payne et al, 1984).

Pigs

9.4 The use of straw in pig feed has generally been considered undesirable (Braude and Lerman, 1972; Kempen and Grimbergen, 1977; Farrell, 1973). However, a considerable research effort has been made, notably in the former East German republic, on the possible use of chemically treated straw meal for pigs. (Betzin and Bergner, 1983; Bergner and Betzin, 1983; Bergner, 1988; Munchow, 1989)

Poultry

9.5 Straw seems to be an unlikely source of food for poultry but there have been a few published references to such possible use. The use of straw which has been fermented by a fungus has been investigated in Czechoslovakia (Zelenka et al, 1983) and the use of chemically treated straw in poultry rations has been reported from California (Dvov and Ben-Ghedalia, 1987).

Dogs

9.6 Mention should also be made of trials which have been carried out on the possible inclusion of straw in dog food (Fahey et al, 1990). American studies on English Pointer dogs suggested that 6% of alkaline hydrogen peroxide treated straw could be included in meat-based, extruded dog diets, while only slightly reducing nutrient digestibility.

Human nutrition

9.6 The use of straw for human nutrition must seem at first sight to be most unlikely. Nevertheless, there has been interest in this possibility, mainly because of the potential value of straw-derived fibre in digestive processes and of the effect which the inclusion of straw would have in reducing the calorific level of certain foods. Studies of the effect on human digestion of dietary fibre (Theander and Aman, 1979; Floren and Nilsson, 1982) are concerned rather with fibre obtained from bran. However, an intriguing recent paper from the United States deals with fibre obtained from alkaline hydrogen peroxide-treated wheat straw (AHP-WS) (Jasberg et al, 1989).

9.7 The AHP-WS was prepared by a method which has been described in some detail, (Gould[a], 1985; Gould et al, 1989). The treated straw was washed with water and then dried in a forced-air oven at 40°C for 24 hours. The dried straw was then ground through a 0.5mm screen to give a fluffy fibrous material that was off-white to pale yellow in colour.

9.8 This AHP-WS was added to, or substituted for, normal flour in a recipe for chocolate layer cake. Additions and substitutions at various levels were tested.

9.9 The results of the tests are summarised by the authors of this paper as follows:

'Our data indicate that AHP-WS may offer significant potential as a high-fibre, non-caloric additive for layer cakes. AHP-WS can be used to replace a large portion of the flour normally present in cake formulations, reducing calories and increasing dietary fibre content. Alternatively, the addition of low levels of AHP-WS to cake formulation can increase cake volume and allow the use of extra water. In both cases, it is possible to produce highly acceptable cakes with regard to overall flavour quality, mouth feel, texture, and the absence of off-flavours'.

9.10 The authors go further in saying that, 'Preliminary studies in our laboratory indicate that peroxide-treated cellulosics can be successfully incorporated into a variety of baked products, including batter-based foods such as pancakes and donuts, as well as dough-based, yeast leavened foods such as breads and rolls'.

Ensiling with beet tops, grass and turnips

9.11 Trials concerned with the mixing of straw with a variety of other materials, loosely called ensiling, have been reported from various countries. Mixing straw with sugar beet tops has been carried out with some success in the United Kindgom and scientific trials have been reported from Denmark (Pedersen and Witt, 1978). They found that cut or milled straw prevented seepage loss of organic matter and crude protein from clamps. Trials in the Netherlands over a period of years showed that straw in layers in sugar beet top silage absorbed 2.4 times its own weight of effluent. It was calculated that it would need to be added on a 1:1 ratio to absorb all effluent; and the nutritive value of the soaked straw was low (Corporaal, 1987).

9.12 Many trials have been carried out on mixing straw with grass; straw can be an effective absorbent of effluent but it reduces the nutrient value of the bulk. (Rydin, 1964; Woolford et al, 1983.) Treating the straw before mixing helps to overcome this disadvantage, but at a cost. In recent Scottish trials, straw was mixed with an enzyme and with urea in an attempt to improve the nutrient quality of the silage (Jakhmola et al, 1990); the addition of urea gave positive results but the enzyme treatment did not show a significant effect.

9.13 Trials in which wheat straw, either treated or untreated with ammonia, was ensiled with turnips, have been carried out in Oklahoma (Hart and Horn, 1987). Straw was found to improve the preservation of the turnip silage but the digestibility of the straw was not improved.

Ensiling with abbatoir waste, 'swine waste', industrial waste liquids and urine

9.14 In Virginia, USA, straw treated or untreated with sodium hydroxide was ensiled with slaughter house blood and ruminal contents. (El-Yassin et al, 1991), and the products fed to sheep. These workers conclude that, 'Ruminal contents and blood ensiled with straw can be used as a ruminant feed'.

9.15 In Mexico, investigations have been carried out into ensiling of wheat straw with 'swine waste', the product being fed to sheep (Iniguez-Covarrubias et al, 1990). These workers report that, after 17 days of fermentation, 'total coliforms were completely destroyed and clostridia and aerobic bacteria tended to be decreased by ensiling'.

9.16 Trials have been carried out in India, treating wheat and rice straw with industrial waste liquids (Nagra and Langar, 1984). These workers found that some alkaline cotton textile effluents increased the <u>in-vitro</u> digestibility of straw in much the same way as sodium hydroxide and they suggest that such effluents 'have a potential use for the treatment of straw/stovers'.

9.17 Workers in Bangladesh found that treating straw with animal urine was as effective as treating it with urea (Hague et al, 1983). This, they point out, 'is important in the Asian context as animal urine is normally wasted and fertiliser grade urea is relatively expensive'.

10. MISCELLANEOUS USES

10.1 Straw has been used for an almost infinite variety of purposes from archery targets to marquetry. Among those that have been mentioned in recent publications are the following:-

Effects on algae and water quality

10.2 An unusual use for straw has come to light, almost accidentally during the past few years (Welch et al, 1990; Ridge and Barrett, 1992). It was noticed that decomposing barley straw in a canal reduced the spread of filamentous algae. The growth of such algae becomes a serious nuisance, and possibly dangerous, in some seasons; if barley straw can provide a means of control, this is well worth investigating. It is still not known exactly how the inhibition of growth occurs, but the technique is considered promising and could lead to a demand for an appreciable quantity of straw.

10.3 A seemingly contradictory effect of straw on algae has been reported from the International Rice Research Institute in Manila (Barthakur et al, 1983). There it was found that surface-applied rice straw in waterlogged rice fields provided energy which enhanced the growth of blue-green algae.

10.4 At the Amey Roadstone Company's Wildfowl Centre at Great Linford in Buckinghamshire, a technique has been developed (Street, M, 1984) to enrich lakes made in old gravel pits using waste barley straw at a minimium rate of 10 t/ha. The straw bales are broken open, teased apart and floated on the water surface. The straw sinks to carpet the lake bed. The soluble nutrient salts and sugars rapidly leach out and the presence of the straw produces a major change in the lake bed, providing much more cover for invertebrates. It also has a binding effect on the fine deposits on the lake bed and thus improves water clarity and speeds the colonisation by rooted submerged plants.

Filtering heavy metals

10.5 Straw has also been used as a filter for removing heavy metals from water. In Denmark, experiments showed barley straw to be slightly inferior to activated carbon in adsorbing heavy metals when packed in columns. Such a column, saturated with copper, was regenerated with dilute acid so that it could be reused at least five times (Larsen and Schierup, 1981).

10.6 Work reported from India (Kumawat and Dubey, 1991) has demonstrated the sorghum straw is an 'efficient remover of metal from waste water'; although not as efficient as activated carbon for this purpose it is considered to be an important alternative in view of its availability and cheapness.

Absorbing spillages

10.7 Another use for straw as an agent for absorbing noxious spillages has also been developed during the past few years (Frogbrook, 1990). In this system a net-enclosed mat is produced from round bales, in 40 metre lengths, and these mats can be used, for instance, to protect coastlines from oil spillage and to soak up oil from polluted water.

10.8 Another unusual use of straw on soil is cited in a Danish paper (Hvass, 1985). Straw mats on a plastic backing have been used to defend trees planted along streets from road salt splash.

Lignin and furfural

10.9 A great variety of chemicals can be extracted or made from straw. Lignin is one such and methods for its extraction and possible uses for it, including use as a binder for particle board, have been described in a German paper (Nimz and Casten, 1986). This same paper considers the products to be derived from hemicelluloses, including furfural.

10.10 The lignin content of wheat straw internodes and its chemistry has also been investigated recently by workers in Australia (Lam et al, 1990); they were concerned with the effects of lignins on digestibility but their conclusions will apply to other aspects of straw use.

10.11 The lignin in straw has a variety of potential uses (Anon, 1984). Most of the research and development on this material has been done on lignin from timber but the lignin from straw presents similar opportunities.

Carbon dioxide

10.12 The production of carbon dioxide (CO_2) from straw, for the purpose of atmospheric enrichment in glasshouses used for cucumber production, by a simple process of composting it with ammonium nitrate has been pioneered by a grower at Littlehampton (Hayman, 1987). Paraffin burners were used to supplement CO_2 supply when production from the straw was slow, or lost through vents.

Reinforcing polyester composites

10.13 The possible use of straw to reinforce rigid urethane-foam was reported in the United States some years ago (Kumar and Lottman, 1972). More recently, research workers at the University of Bath have described the use of straw fibres in reinforcing polyester composites (White and Ansell, 1983). This work considers in detail the nature of straw-fibres and their use in composite manufacture.

Alkaline ash

10.14 The possibility that the ash from burned agricultural wastes such as straw could be used as a substitute for an alkali such as sodium hydroxide has been considered by some research workers (Adebowale, 1985). In feeding trials it was found that maize straw treated with ash from cocoa pod husk gave better daily gains than untreated straw, but less than those from NaOH-treated straw.

Amorphous silica and silicon carbide

10.15 A method of producing amorphous silica from rice straw has been described by Indian workers (Chakraverty and Kaleemullah, 1991). The straw in these experiments was pre-treated with hydrochloric acid and the ash was produced at a temperature of 500°C. The production of silicon carbide from rice straw has been described by other Indian research workers (Patel and Kumari, 1990) in a short note.

Graft polymerisation

10.16 Graft polymerised wheat straw has been the subject of recent research (Fanta et al, 1987). The United States workers have succeeded in grafting acrynonitrile onto ground, washed wheat straw. It is not clear whether this process will enable better economic use to be made of the straw but the American experiments showed that conversion of the cellulose in straw by the enzyme cellulase could be improved by such polymerisation.

11. GENERAL COMMENTS, RECOMMENDATIONS AND CONCLUSIONS

General comments

11.1 From the foregoing chapters it will be clear that there has recently been an immense amount of research and development on many aspects of straw utilisation. Some of the lines may appear to readers to be more promising than others, but some of the most unlikely-looking projects may prove in the end to be commercial successes.

11.2 Very much depends today on the effects of legislation. The success of Danish straw-fired district heating is in part due to heavy local taxes on fossil fuels. A European tax on such fuels, even if at a lower level, can affect the economic viability of straw as a fuel. A recent French publication (Gatel et al, 1992) shows how the economics of ethanol production from biomass may be affected by changes in the EEC setaside regulations. The Austrian straw-fired 'French-fries' factory at Hollabrun may owe some of its success to favourable capital cost write-off provisions.

11.3 It will also be clear from the text of this review that projects for straw utilisation vary greatly in size, from those requiring only a few tens of tonnes to those requiring hundreds of thousands of tonnes. However, it would be a mistake to neglect the smaller projects - they can add up to require economically important quantities of straw.

11.4 The review has concentrated upon research and development which has featured in printed publications. However, there have been other interesting developments which have been carried out inconspicuously, often on farms, or which have not yet been reported in the technical press. The growth of the packaged straw pet litter trade is a case in point. Other examples are the manufacture of straw-based firelighters, pioneered on an Essex farm; the development of methods of harvesting and combing wheat 'reed' for thatching; the design and construction of bale compression machinery in Lincolnshire, and a revival in the making of straw mattresses near Bremen in Germany.

11.5 Important research and development at the Silsoe Research Institute on machinery for the handling, slicing and conveying of straw for processing (Plate 12) which is of immediate relevance to the new St. Regis straw pulping plant in South Wales, has not been fully reported; it is being mentioned in the farming press as this Review is being completed (Anon, 1992).

11.6 Similarly, work at the new Biocomposite Centre at Bangor, which may have considerable influence on future straw use, is only beginning to receive publicity. (Robson, 1991).

11.7 New ideas are continually coming forward. As this Review is being completed, a new type of 'Strawcrete' is being experimentally developed: ground straw is coated with a cement matrix and formed into fire-resistant panels (Patent No. 9203243.2) which may eventually find a large market.

11.8 Many concepts have appeared highly promising in the past but they have made no headway because they could not attract funds for often expensive development and promotion. This is where an organisation such as the proposed Straw Development Association could prove helpful. The Home-Grown Cereals Authority itself has shown its interest by commissioning this Review.

Recomendations

11.9 Potential industrial users of straw have always been concerned about the reliability of supply (Truman, 1974). A fundamental difficulty has been the speculative nature of the market. In some years there have been shortages of straw which drive up the price and make potential future users wary. In other years, too much is baled, the farmer gets little return for his effort and is deterred from baling straw in future years. It is suggested that a survey should be made, covering at least two seasons, to determine just how much straw is baled, how it is used or marketed and how much is spoiled. The results of such a survey would show how much money and effort can be wasted in this way, and would emphasise the need for firm contractual arrangements in future straw marketing. There would be an opportunity while carrying out this survey, to obtain reliable information on actual yields of baled straw.

11.10 MAFF should be encouraged to resume its enqiries into straw yields as part of the system of quarterly returns.

11.11 The Review of Research needs to be kept regularly up-to-date since there is so much continuing research and development in straw utilisation, world-wide.

11.12 The series of international straw conferences, begun by MAFF at Oxford in 1974 and carried on since 1987 under the sponsorship of PIRA and the NFU, is a valuable way of publicising the possibilities for increased straw use, and these conferences should be continued.

11.13 Certain aspects of the development of straw use should be encouraged in every possible way. One promising outlet for large quantities of straw is for use in composting with materials such as sewage sludge or abattoir waste. Research and development into the making and economic utilisation of such compost should be supported.

11.14 Similarly, there is an excellent prospect for more straw to be used for pulping for paper in the UK and there is a need to encourage further development work into the reliable supply of straw of high pulping quality to paper mills.

11.15 There have already been remarkable developments in the collection, packaging, storage and transport of straw - largely in response to the large-scale requirement for straw in recent years for the BOCM/Silcock treatment factories and for the expanding synthetic mushroom composting factories. However, there is still a need for further development in systems of straw collection, fractionation, densification and transport.

Conclusion

11.16 There is no doubt that there are rewards to be had for cereal growers by appreciably increasing the offtake of straw from farms at an economic price. It is not unreasonable to aim at a large market for dry straw, delivered to factory, at a price of say, £30 per tonne, in current market conditions. With a yield of 1.5 tonnes per acre, the increased gross margin to the farmer is not enormous but it is worth having at a time when grain prices are slipping.

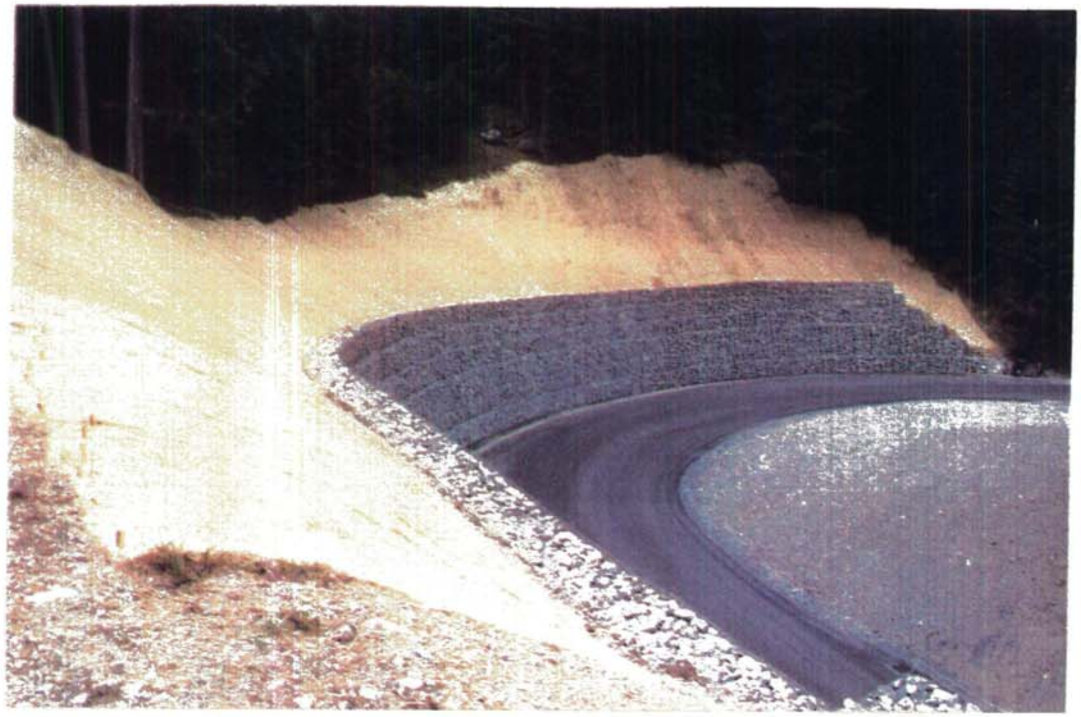


Plate 1: Straw matting pinned to a new road cutting near Davos, Switzerland to control erosion.

Plate 2: Spreading straw mulch round young apple trees in Kent to improve moisture supply and to control weeds.

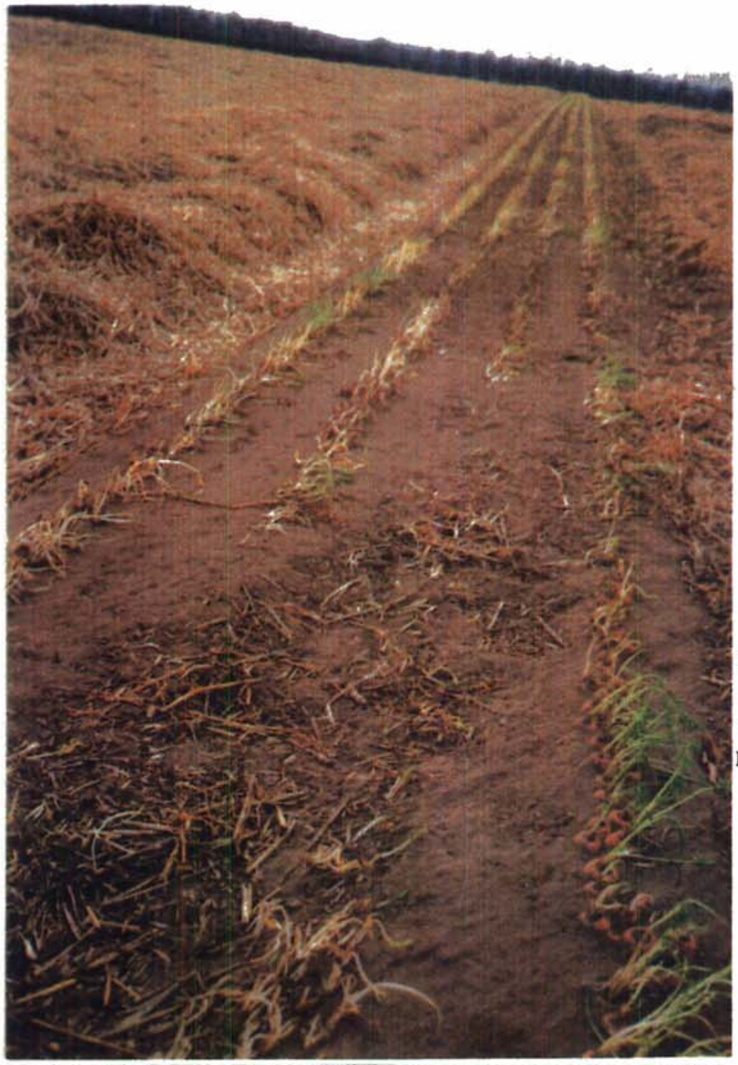


Plate 3: Large quantities are now used to cover carrots for winter storage, as in this field at Newark, Notts.

Plate 4: Mulching strawberries to control flowering date

Plate 5: Composting sewage sludge at Little Marlow, Bucks.

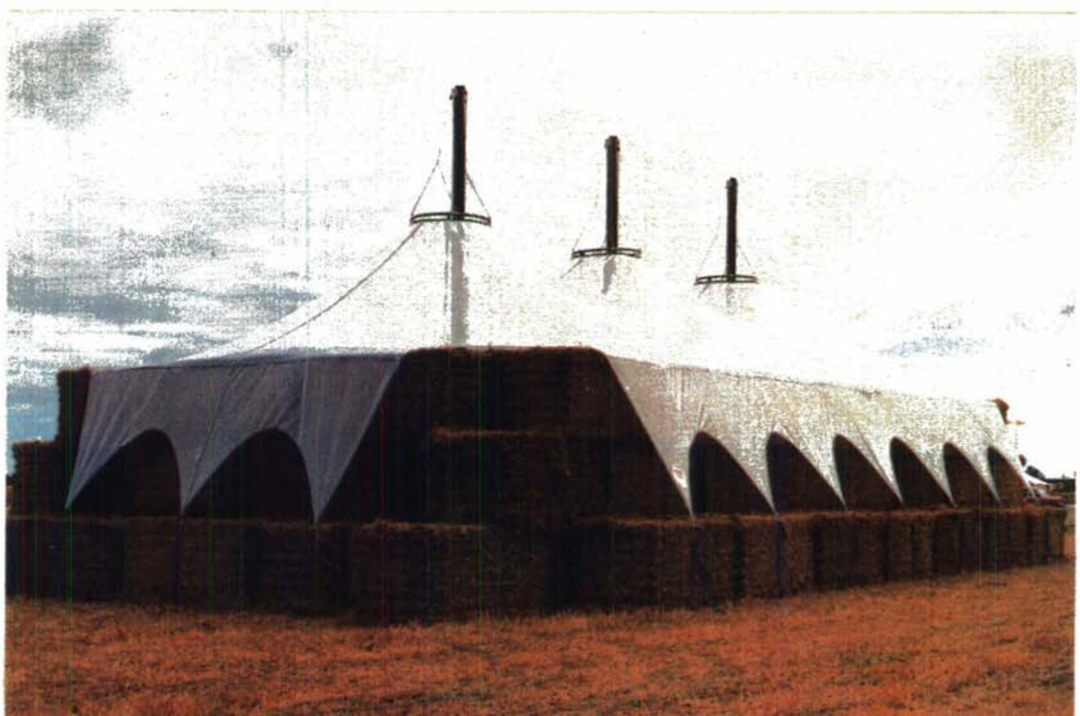


Plate 6: Experimental outdoor pig housing - Denmark

Plate 7: Clay-rendered straw building in the United States

Plate 8: Straw briquettes produced from the light straw fraction at Dunauijvaros Paper Mill, Hungary

Plate 9: 3,000 tonnes of straw are used per annum to cook 36,000 tonnes of potatoes at Hollabrunn near Vienna, to supply 50% of Austrian french-fries.

Plate 10: Oyster mushroom production on straw bales at Chaource, Central France

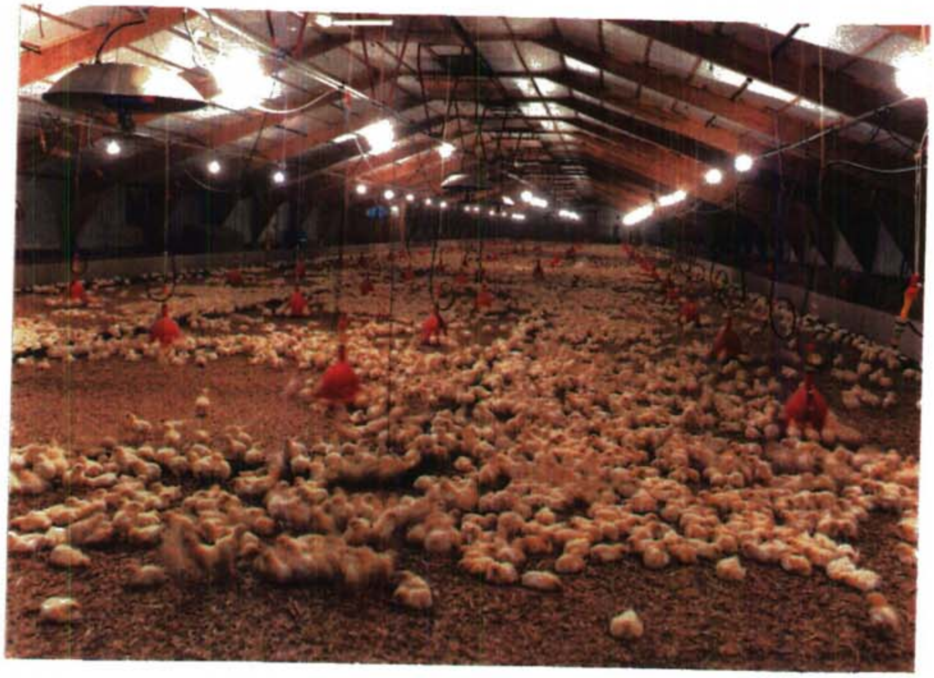


Plate 11: Properly prepared straw has proved to be a good substitute for wood shavings in broiler litter

Plate 12: A corer developed at Silsoe Research Institute for big bale sampling.

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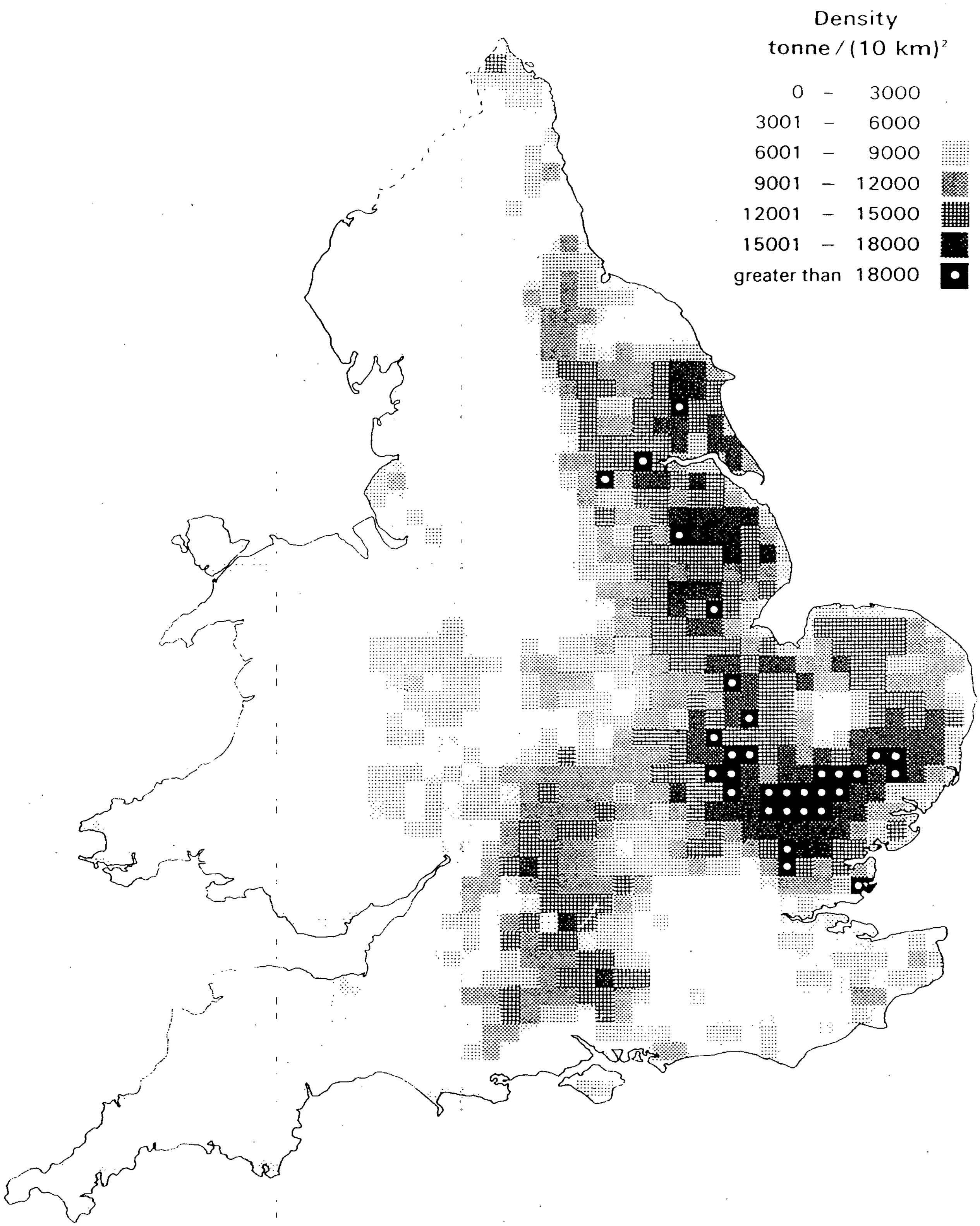
APPENDIX I - Density of total cereal straw production in England and Wales, tonne of dry matter per 10 x 10 km square grid



Source: Straw Disposal and Utilisation. MAFF, London, 1984.

Ministry of Agriculture, Fisheries and Food

MAFF

STATISTICS

STATS 209/91

6 DECEMBER 1991

STRAW DISPOSAL SURVEY 1991 - ENGLAND AND WALES

The results of the 1991 Straw Disposal Survey are given below. Details of the straw harvested, ploughed in or burned were obtained from a controlled sample of about 1,000 cereal growing farms and the results grossed up to give estimates for England and Wales. The figures are subject to sampling errors.

The following table shows, for each main cereal crop, the pattern of straw disposal in 1991, with comparative figures for 1990. A longer time comparison of percentages baled, ploughed and burned indicating trends over seven years, can be seen in the charts attached.

thousand hectares

	Straw baled and removed		Straw ploughed in or cultivated		Straw burned in the field (a)		Total (b)	
	1990	1991	1990	1991	1990	1991	1990	1991
TOTAL	1907.1 *61.4%*	1745.3 *58.7%*	667.8 *21.5%*	789.9 *26.6%*	533.3 *17.2%*	434.1 *14.6%*	3108.3 *100%*	2969.2 *100%*
Wheat	844.3 *44.6%*	811.9 *43.4%*	566.2 *29.9%*	669.7 *35.8%*	484.3 *25.6%*	389.1 *20.8%*	1894.8 *100%*	1870.7 *100%*
Winter barley	699.1 *86.3%*	659.1 *84.9%*	74.2 *9.2%*	84.6 *10.9%*	36.4 *4.5%*	32.6 *4.2%*	809.8 *100%*	776.3 *100%*
Spring barley	297.1 *90.2%*	209.9 *84.6%*	22.5 *6.8%*	29.3 *11.8%*	9.6 *2.9%*	8.9 *3.7%*	329.2 *100%*	248.1 *100%*
Oats	66.5 *89.4%*	64.4 *86.9%*	4.9 *6.5%*	6.3 *8.5%*	3.0 *4.1%*	3.4 *4.6%*	74.4 *100%*	74.1 *100%*
Number of holdings (thousands)	54.5	50.9	15.0	19.1	13.3	14.1	61.0(c)	59.1(c)

Notes
(a) Excluding area of stubble burned after removal of straw.
(b) Total crop areas for 1990 are based on final figures from the June census. For 1991 the latest available figures are used.
(c) The numbers of holdings disposing of straw in different ways add up to more than this total because some holdings dispose of straw in more than one way.
Estimates for minor holdings are not included.
Totals may not agree with the sum of their components due to rounding.

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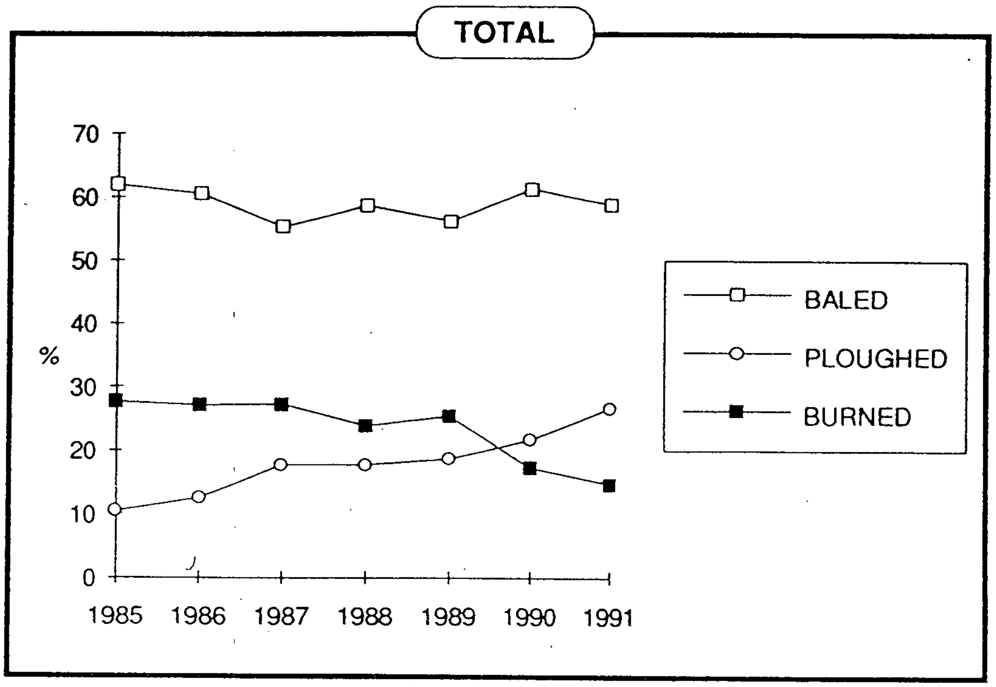
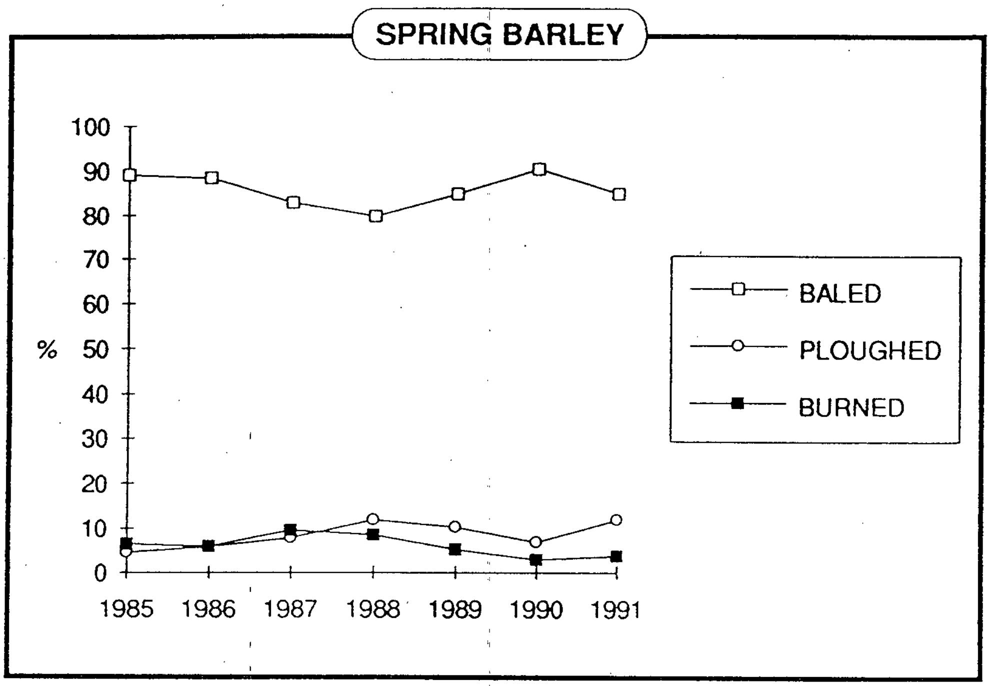
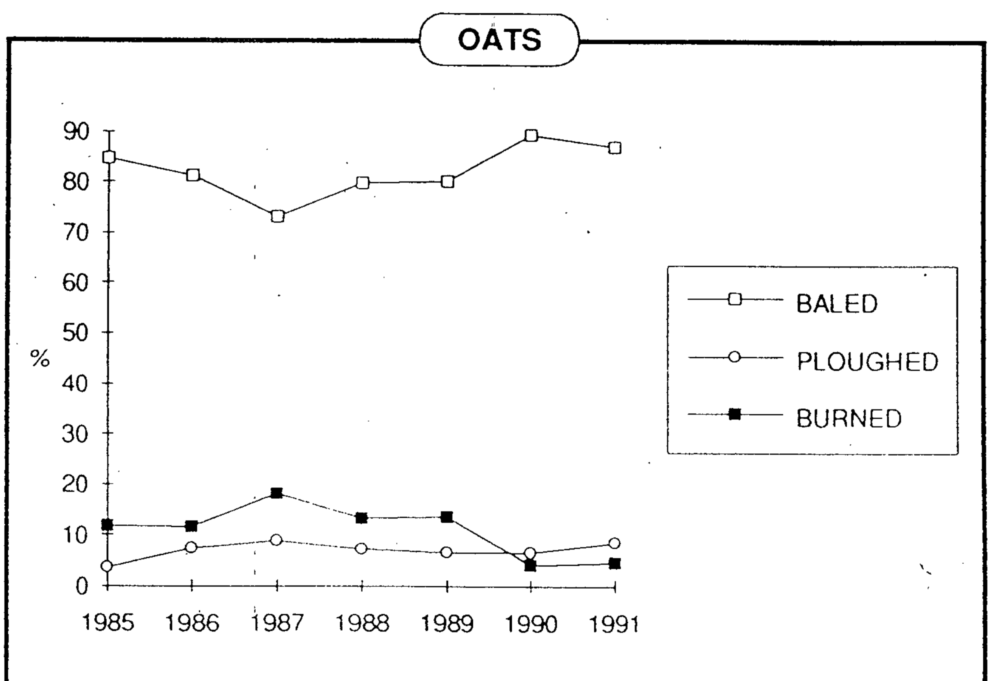
APPENDIX III(a) - Recent trends in straw disposal - all cereals



Source: MAFF Statistics,

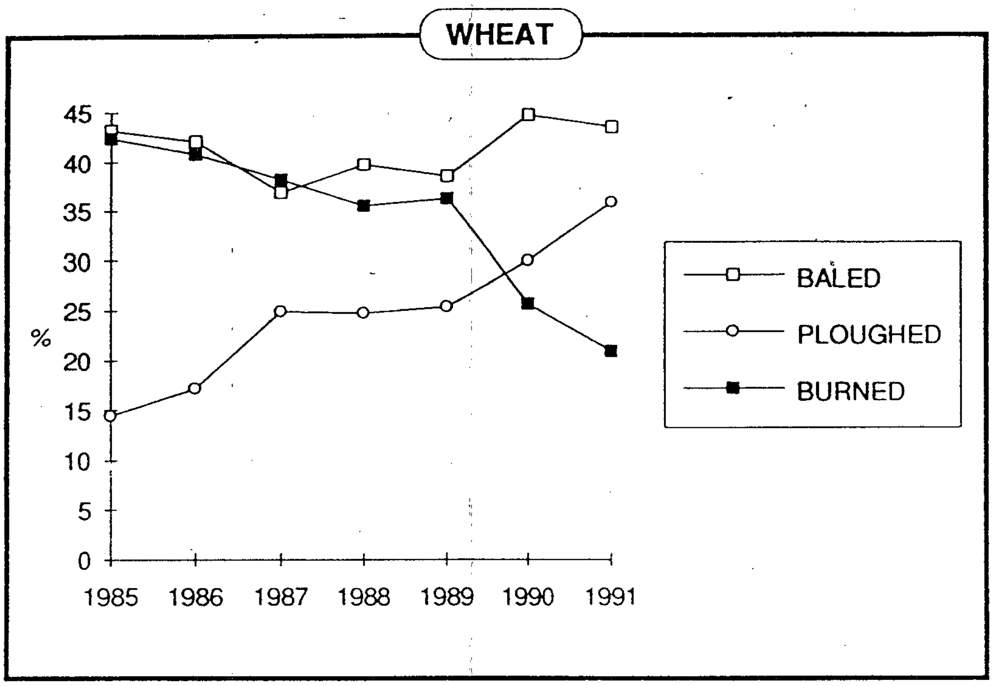
APPENDIX III(b) - Recent trends in straw disposal - spring barley and oats

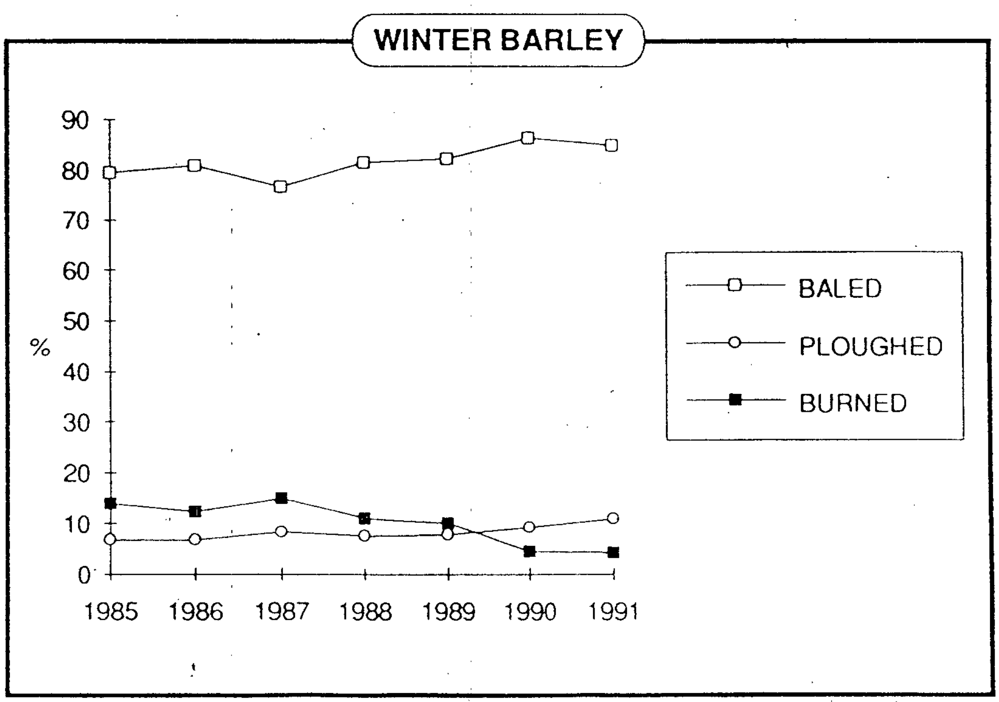




Source: **MAFF** Statistics.

APPENDIX III(c) - Recent trends in straw disposal - wheat and winter barley





Source: MAFF Statistics.

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