July 2014

Research Review No. 81

Straw incorporation review

Fiona Nicholson[1], Daniel Kindred[2], Anne Bhogal[1], Susie Roques[1], Jonny Kerley[2], Susan Twining[2], Tom Brassington[3], Peter Gladders[2], Helen Balshaw[1], Sarah Cook[2] and Steve Ellis[4]

[1]ADAS Gleadthorpe, Meden Vale, Nottinghamshire NG20 9PD

[2] ADAS Boxworth, Battlegate Rd, Boxworth, Cambridgeshire, CB23 4NN

[3] ADAS Wolverhampton, Pendeford House, Pendeford Business Park, Wobaston Road, Wolverhampton WV9 5AP

[4]ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire YO17 8BP

This review was produced as the final report of a three month project (219-0002) which started in April 2013. The work was funded by a contract for £20,000 from HGCA.

HGCA is the cereals and oilseeds division of the Agriculture and Horticulture Development Board.

CONTENTS

1. Abstract

The traditional uses of straw as animal bedding or feed are nowadays being supplemented by new markets for straw as a bioenergy crop or renewable material. Farmers are also becoming more aware that incorporating straw not only provides a valuable source of plant nutrients, but can also help to maintain or build soil organic matter (SOM) levels. The decision on whether to remove and sell straw or to incorporate it into the soil is farm specific and depends on a number of factors.

The aim of this review was to examine the environmental, economic and practical impacts of wheat and oilseed rape (OSR) straw incorporation versus removal, to facilitate the decision making process for farmers and to provide information for policy makers.

Soils. Long-term studies have indicated that straw incorporation can increase soil total nitrogen (N) reserves by *c*.7% over the long term (8+ years), although this has not been shown to have a significant effect on crop N fertiliser requirements. Straw incorporation also returns significant amounts of potash, and some phosphate, magnesium and sulphur. Based on 2013 prices, the nutrient value of wheat straw was around £3/ha for phosphate and £17/ha for potash (plus £15/ha for magnesium). Whilst the phosphate and potash value will be realised on soils at Index 2 or less (except for potash-releasing clay soils), the Mg value will only normally be realised on deficient soils (Index 1 or below).

Whilst a number of studies have shown modest improvements in SOM and soil physical properties following medium to long-term straw incorporation (i.e. >8-10 years), there was little evidence of short-term impacts on soil quality, workability or yield. Whilst it was not possible to ascribe an economic value to these changes, the importance of maintaining or building SOM levels is recognised. Where SOM levels are low (<5% organic matter), it is more effective to build levels by the addition of bulky organic materials such as solid livestock manures, compost or biosolids.

Agronomy. In most situations, straw incorporation has little impact on weed, pest and disease control. However, where slug populations are high, straw incorporation could increase costs by *c*.£20/ha, and where oilseed rape disease (i.e. light leaf spot, verticillium wilt and sclerotinia) pressure is high by *c*.£30-100/ha.

Operational issues. The operational impacts of straw removal or incorporation (such as delays to cultivation and subsequent crop establishment) should be considered on an individual farm and field basis. In principle, straw removal could reduce fuel and machinery wear costs by around £5/ha (by not chopping straw), although importantly, the risk of soil compaction during straw removal can be substantial on medium/heavy soils in wet years, costing up to £55/ha to remedy.

A decision support tree has been developed to guide growers through the factors they need to consider when deciding whether to remove and sell their straw or to incorporate it into the soil.

2. Introduction

Straw can be seen as a valuable part of a farm system (e.g. as livestock bedding), an output for sale or as a ‘waste’ disposal problem. On many mixed arable and livestock farms, where straw is used on farm for feed or bedding, it is an integral reason for growing the crop, with the straw valued as highly as the grain. At the other extreme, arable farmers may see it as a nuisance that costs time and money to deal with, and that hampers establishment of the following crop; indeed some would wish to see a return to the days of straw burning to remove these problems. For those who choose to incorporate straw, there are potential benefits of increasing soil organic matter (SOM) and thus maintaining good soil structure, as well as providing a valuable source of plant nutrients such as phosphorus (P) and potassium (K). On mixed farms, where straw is used for animal bedding, many of the perceived problems of straw removal are usually avoided, as in the long run the organic matter and nutrients in the straw are generally returned to the arable land with livestock manures. On arable farms, straw sales provide a valuable revenue stream whether it is sold to local livestock farmers, to merchants or for use as a bioenergy feedstock or in bio-renewable products.

Interest in the size of potential production and existing utilisation of straw has largely been driven by the potential new markets of bioenergy and biorenewables. Straw is perceived as an under-utilised resource with a low GHG footprint, and thus as a suitable resource for a range of industries which seek to provide GHG mitigation by displacing fossil-based feedstocks. Some of these industries are already well established, such as dedicated straw-burning power stations (e.g. Ely) or plants where straw is co-combusted with coal (e.g. Drax). Current straw use is estimated to be at least 0.3 Mt/yr, increasing by an additional *c.*0.5 Mt/yr if three more planned power stations come on stream (Brigg, Sleaford and Tansterne; Stoddart & Watts, 2012). Straw may also be used to a limited extent as a co-feedstock in some anaerobic digestion facilities producing biogas and/or electricity. Straw has been widely cited as a potential feedstock for advanced biofuels (e.g. HGCA current project 3400). If and when suitable technologies become commercially available to turn lignocellulosic material into liquid biofuels (e.g. bioethanol or biobutanol) it has been estimated that over 1 Mt straw could be used for this purpose (Nattress *et al*., 2011; Kretschmer *et al*., 2013). Straw also has a potential increasing market as a renewable material for the construction industry and in manufacturing (e.g. HGCA current project 3351).

In contrast, some researchers have considered the GHG mitigation potential of increased carbon (C) sequestration via straw incorporation into the soil (Smith *et al*., 1997). Powlson *et al*. (2011a, 2012) argued that the potential for straw incorporation to result in significant C sequestration was limited and it was important to consider the alternative fate of the straw. Indeed, both Kilpatrick *et al*. (2008) and Powlson *et al*. (2008) argued that greater environmental savings could be made by using straw for energy generation (leading to larger reductions in CO_2 emissions compared with coal burning) than by savings gained through C sequestration from soil incorporation.

This study was conducted in response to an HGCA call to review the economic and environmental impacts of chopping and incorporating straw in into the soil in comparison with baling and removing it for subsequent sale, to help growers to decide which approach they should adopt. The decision making process is not straightforward as it depends on the individual farm circumstances. The most important driver is usually the market value of the straw, which varies regionally and from year to year. Other factors to be considered include the farming and cropping system employed; the availability and costs of baling and straw removal machinery; the risks and impacts of delayed cultivations or soil compaction; and whether establishment of the following crop is helped or hindered by straw incorporation. The perceived value of incorporating straw is influenced by the soil nutrient status, texture and organic matter content, with agronomic factors such as pest, weed and disease control also important considerations.

2.1. Project objectives

To conduct an evidence-based literature review of the potential environmental and economic impact of wheat and OSR straw incorporation vs. removal for UK arable situations in order to support growers in decision making and to provide information for policy makers, especially on the different uses of straw.

Objective 1: Soil impacts

To review the impact of straw incorporation/removal on soil physical, chemical and biological properties (i.e. organic matter, structure, bulk density, compaction, nutrient status, etc.) in order to estimate, where possible, the economic and environmental consequences of straw fate for a range of situations.

Objective 2: Agronomic impacts

To review the agronomic impacts of straw incorporation/removal, including impacts on weeds, pest and disease incidence, severity and control, crop establishment, yields and quality.

Objective 3: Operational impacts

To consider the mechanical and logistical implications of straw incorporation/removal including fuel usage during harvesting, impacts on ease of subsequent cultivations (especially min-till operations) and risks of delayed cultivations from delayed straw removal and/or soil damage through compaction.

Objective 4: Cost benefit evaluation

To provide an overall appraisal of the economic value (£/ha) and environmental consequences (greenhouse gas (GHG) /ha) of straw incorporation/removal for a range of soils and farm systems. To produce a simple decision support guide to assist farmers/growers in the management of crop residues.

2.2. Previous research on straw incorporation vs removal

In the years leading up to and following the ban on cereal straw burning, a large amount of research was conducted into the agronomic impacts of straw incorporation (e.g. HGCA, 1988; MAFF, 1984). This largely focused on the mechanical feasibility and agronomic consequences of straw incorporation, and a number of experimental sites were established, e.g. sites at Rothamsted and Woburn (Johnston *et al*., 2009), as well as Morley and Gleadthorpe (Nicholson *et al*., 1997).

Whilst this past information is still largely relevant, it needs to be re-interpreted in the context of a number of changes in modern farming systems. Straw chopping techniques have changed; straw choppers are now ubiquitous on modern combine harvesters and can be set in or out of work easily, whereas, in the 1980s, straw was mostly chopped by separate choppers towed by a tractor. Modern choppers cut straw into shorter lengths than in the 1980s and distribute it more evenly across the combine width. Chaff spreaders on modern combine harvesters spread chaff across the combine width, whereas previously it would fall immediately behind the combine and could not be effectively spread once on the ground. Cultivation and establishment techniques have also changed, with greater use of minimum tillage and modern cultivation equipment that has been designed to deal with chopped straw and to incorporate it effectively. The use of auto-cast and sub-cast systems is now widespread for the establishment of OSR. Moreover, the relative importance of diseases, weeds and pests may have changed since the previous work was undertaken. There has been very little recent work specifically addressing the agronomic impacts of straw incorporation, so it is therefore important to assess the large amounts of research conducted in the 1980s in the light of current farming practices and problems.

The more recent work on straw incorporation has focussed on impacts on SOM and soil health, (e.g. Defra project SP0530: Soil-QC project evaluating the effects of organic carbon (OC) additions on soil properties; Bhogal *et al*., 2009), and the critical evaluation of straw incorporation as a means of sequestering C (e.g. Defra project SP0561: Effects of reduced tillage and organic material additions on soil carbon; Bhogal *et al*., 2008). These recent studies often rely on the long term experimental sites set up before the burning ban, which have proved invaluable when assessing the longer-term impact of straw incorporation/removal on soil properties (e.g. Bhogal *et al*., 2009, Powlson *et al*., 2011a) and have played a central role in the evaluation of straw incorporation as a means of sequestering C for climate change mitigation (e.g. Bhogal *et al*., 2008;

Powlson *et al*., 2012). Evidence from these and other studies suggests that there is a trend for increasing SOM where straw is incorporated, but that the increases are usually small and differences between straw incorporation versus removal are often not statistically significant (Powlson *et al*., 2012). However, impacts on the soil microbial biomass can be much larger, which in turn influences both soil nutrient cycling and the formation of stable aggregates (Powlson *et al*., 2011b). Indeed, increases in SOM have been associated with increased water holding capacity, porosity, strength and nutrient status (Bhogal *et al.*, 2009), although placing a value on these additional benefits is challenging. In the light of this, Powlson *et al*. (2011b) cautioned against the annual removal of straw, suggesting this would lead to deterioration in soil physical properties (unless other organic materials were applied).

3. Soil impacts

The decision on whether to incorporate or remove straw has implications for the soil in terms of: i) the removal or return of nutrients; ii) impacts on the SOM content and subsequent effects on soil physical properties and iii) negative effects such as altered trafficking regimes on the potential for soil compaction.

3.1. Soil nutrients

Straw incorporation returns valuable nutrients back into the soil, particularly P and K, leading to potential economic savings through reduced additions of organic and inorganic fertilisers (HGCA, 2009). The value of these nutrients should be an important consideration in deciding soil fate, especially with the increasing price of fertiliser. However, cereal straw can cause the ‘lock up’ of N in autumn as the decomposition of the C-rich straw causes soil microbes to take available nitrate or ammonium nitrogen out of the soil solution, potentially slowing the growth of seedlings over winter and adding to the need for autumn N fertiliser (Jenkinson, 1985).

3.1.1. Phosphorus, potassium, magnesium and sulphur

Straw contains useful quantities of potash (K_2O), phosphate (P_2O_5) and magnesium oxide (MgO). If straw is incorporated these nutrients are returned to the soil thus reducing the requirement for inorganic fertilisers. Typical quantities of nutrients in straw are shown in Table 1, although there is relatively little information on potash and phosphate in rye, pea, bean and linseed straw and on all straw magnesium and sulphur contents. Table 1 shows that 5 t winter cereal straw, for example, can be expected to contain 6.0 kg P_2O_5, 47.5 kgK_2O, 6.5 kg MgO and 6.5 kg SO_3.

Table 1. Nutrient content of straw (kg/t fresh weight) (Defra, 2010; HGCA, 2009).

	Phosphate (kg P_2O_5/t)	Potash (kg K_2O/t)	Magnesium (kg MgO/t)	Sulphur (kg SO_3/t)
Winter wheat/barley straw	1.2	9.5	1.3*	1.3**
Spring wheat/barley straw	1.5	12.5	1.2*	nd
Oat straw	1.6	16.7	2.2*	nd
Oilseed rape straw	2.2	13.0	nd	nd
Rye straw	2.1*	10.0*	1.0*	nd
Pea straw/haulm	3.9*	20.0*	1.7*	nd
Bean straw/haulm	2.5*	16.0*	1.8*	nd
Linseed straw	1.3*	9.2*	nd	nd

*best estimates from relatively few samples
**based on two samples from an ADAS study
nd; no data

The potash content of straw can vary substantially; for example, Withers (1991) reported that there was a tendency for straw K concentrations to be higher in dry years than in wet years and that straw K concentrations tended to increase with increasing rates of fertiliser N. Higher than average rainfall between crop maturity and baling is likely to reduce straw potash contents as a result of leaching from the straw in the stand or in the swath (Defra, 2010).

Sulphur (S) is an important plant nutrient and there is an increasing risk of deficiency in England and Wales in a wide range of crops including cereals and OSR (Defra, 2010). At a long-term experimental site in Estonia, Kanal (2002) found that wheat straw incorporation increased the quantity of soil water soluble S and increased the N:S ratio of the grain. The S content of wheat straw has also been shown to influence residue decomposition rates in S deficient soils (Stewart *et al*., 1966). Assuming 1.3 kg SO_3/t straw and a price of £0.35/kg for SO_3, the total value of S in straw is less than £1.50/ha (based on a wheat straw yield of 3.4 t/ha). It is questionable how much of this S would be available to the following crop as the S needs to first be mineralised and, like N, is susceptible to leaching loss.

Given the increasing price of inorganic fertilisers, the cost of replacing lost nutrients is a key consideration when deciding the fate of straw. Guidance has previously been produced for calculating the monetary value of the nutrients removed in straw and hence the cost of replacing them with inorganic fertilisers (HGCA, 2009). Table 2 shows the monetary value (£/ha) of straw from a range of arable crops based on average straw yields and nutrient contents (Table 1), with the nutrient value per hectare of straw ranging from £16/ha for OSR to £53/ha for oats (not including the value of S returned with straw).

Table 2. Nutrient content and potential economic value of straw based on average straw yields.

Crop	Straw yield	Phosphate		Potash		Magnesium		Total
	(t/ha)*	(kg/ha)	(£/ha)*	(kg/ha)	(£/ha)**	(kg/ha)	(£/ha)**	(£/ha)
Winter wheat	3.4	4.1	3	32.3	17	4.4	15	35
Spring wheat	3.4	5.1	4	42.5	23	4.1	14	41
Winter barley	2.8	3.4	2	26.6	14	3.6	12	28
Spring barley	2.5	3.8	3	31.3	17	3.0	10	30
Oats	3.0	4.8	4	50.1	27	6.6	22	53
Oilseed rape	1.8	4.0	3	23.4	13	nd	nd	16

*See Table A2
**Using May 2013 Farmbrief fertiliser prices: P_2O_5 = £0.73/kg; K_2O = £0.54/kg; MgO = £3.40/kg (based on Kieserite price of £0.85/kg @ 25% MgO)

These values are only realised if the soil Indices are low enough to warrant regular fertiliser applications (for P and K at Index 2 and below; for Mg at Index 0 only for cereals and Index 0 and 1 for OSR) and those fertiliser applications are adjusted for straw removal. In situations with higher soil Indices, especially for Mg but also P and K, whilst the return of straw keeps the value of the nutrients in the soil and so ‘in the bank’, it can be argued that a greater return on capital could be achieved by selling the straw, and purchasing back the nutrients in the future if required, either as mineral nutrients or through organic additions. The value of Mg should be more fairly counted in rotations where responsive crops are grown (e.g. potatoes, sugar beet). Some clay soils release potash so that the K Index can be maintained without the addition of K fertiliser; on such soils it is not appropriate to value the K in incorporated straw.

Potassium is not usually considered an environmental pollutant, hence K leaching losses from the straw and soil are more of a concern in relation to the effects on plant growth and quality. However, P lost from soils either through leaching or surface run-off may have serious implications for water quality as it contributes to freshwater eutrophication. There has been relatively little research on P losses following straw incorporation; however, Addiscott & Dexter (1994) noted that P in crop residues was ‘safe’ when left on the soil surface. More recently, Bailey *et al*. (2013) postulated that chopping and incorporating straw, rather than baling and removing it, would protect the soil surface from the erosive energy in incident rainfall and thus may be an effective method for reducing P losses. Trials on a sandy soil for one year indicated that treatments receiving 2.5 t/ha straw had reduced runoff, sediment and P losses, although these results were not statistically significant and farm costs were increased by *c.*£19/ha.

3.1.2. Nitrogen

Cereal straw contains less N than grain (*c*.0.6% N in straw compared to *c.*2% in grain) (Nicholson *et al*., 1997). Similarly for OSR, straw N concentrations are typically around 1% compared with around 3% in the seed (ADAS data; Hocking & Mason, 1993; Šidlauskas & Tarakanovas, 2004). Nevertheless, N returns to the soil with straw can be significant, with straw incorporation from a cereal crop yielding 7-12 t/ha of grain contributing 40-70 kg N/ha/yr (Nicholson *et al*., 1997).

When straw is incorporated into the soil it is broken down through microbial activity, with N in mineral form (i.e. ammonium-N and nitrate-N) released in a process termed 'mineralisation'. The rate of crop residue mineralisation depends on a number of factors including the residue C:N ratio and N content, residue placement, degree of contact with the soil matrix, tillage and cropping practices, as well as soil temperature, moisture, aeration and microbial activity (Jensen *et al*., 1997; Silgram & Chambers, 2002). There has been considerable research into the effects of straw incorporation on soil N availability and whether additional N fertiliser is required where straw is incorporated. Generally, a decrease in the soil mineral N pool has been reported due to 'lock up' or immobilised N as the decomposition of the C-rich straw causes soil microbes to take available nitrate or ammonium-N out of the soil solution (e.g. Machet & Mary, 1989; Mueller *et al.* 1994; Robin *et al.* 1994). This can potentially slow over-winter seedling growth and can add to the need for autumn applications of N fertiliser to OSR (though many OSR crops receive autumn N whether or not straw is incorporated). Autumn fertiliser N applications are not permitted to cereal crops in Nitrate Vulnerable Zones (NVZs). Addiscott & Dexter (1994) found that for every tonne of straw incorporated around 10 kg of mineral N became immobilised, with the demand for N mainly occurring within 2-3 months of straw incorporation. Silgram & Chambers (2002) also found that straw incorporation induced temporary N immobilisation. However, both Powlson *et al.* (1985) and Christian & Bacon (1991) reported that application of additional N in autumn to offset possible N immobilisation by decomposing straw could not be recommended based on the results of their experiments. Powlson *et al*. (1985) and Jarvis *et al.* (1989) suggested that straw incorporation could be used to reduce nitrate leaching over winter, and later Nicholson *et al*. (1997) and Silgram & Chambers (2002) confirmed that straw incorporation reduced nitrate leaching by 10-25 kg N/ha at two sites in England. However, other studies (e.g. Catt *et al.*, 1992; Davies *et al*., 1996; Stenberg *et al*., 1999) found the effect of straw incorporation on nitrate leaching was negligible.

As a result of continued straw incorporation, soil organic N reserves are likely to gradually increase over time. In a review of data from a number of long-term studies, Powlson *et al*. (2011b) reported that there was a trend for straw additions to increase soil total N concentrations (in a similar way to soil C), with more soil N where straw had been incorporated than when straw was removed or burnt. The percentage change in soil total N with straw additions ranged from a 10% decrease to a 26% increase (mean 7%). In a long-term study which included three sites where straw had been incorporated for 24 to 30 years, Bhogal *et al*. (2011) found that topsoil total N increased by *c.*5% with every 10 t/ha of OC inputs from organic materials and crop residues. Higher soil total N concentrations are likely to result in greater N mineralisation. Indeed, regular long-term straw incorporation has been found to increase mineralisable N in the soil by up to 40-50% (e.g. Christiensen, 1986; Powlson *et al*, 1987).

Thus in the long-term, straw incorporation may be expected to lead to a decreased need for N fertilisers as the soil organic N reserves are released through mineralisation (Powlson *et al*., 2011b). Indeed Malhi *et al* (2011) found that the long-term retention of crop residues can gradually improve the efficiency of applied N. In general however, this has been difficult to validate. Bhogal *et al*. (2011) found no response of the soil potentially mineralisable N pool to crop residue OC inputs after 24 to 30 years of straw returns. Powlson *et al*. (2011b) reviewed a number of studies which provided contradictory and inconclusive evidence and concluded that "the impacts of straw removal on N cycle processes in temperate regions cannot be regarded as a major consideration in assessing the impacts of removing straw."

Another possible consequence of straw incorporation is the impact on emissions of nitrous oxide (N_2O), which is an important GHG with a global warming potential *c.*300 times greater than CO_2 (IPPC, 2007). Currently, national N_2O emissions are assumed to be related linearly to N inputs (De Klein *et al*., 2007) and emissions are predicted to be the same for all crops and conditions. However, in practice a number of soil factors are known to influence the microbial processes that lead to N_2O emissions including temperature, moisture, OC and available N (Brown *et al*., 2000; Granli & Bøckman, 1994). The impact of crop residue treatment (i.e. cereal straw, pea haulm, sugar beet tops etc., providing contrasting straw C:N ratios) on N_2O emissions is currently being investigated as part of LINK project "Minimising nitrous oxide intensities of arable crop products (MIN-NO; HGCA Project 3474)".

3.2. Soil organic matter and carbon storage

3.2.1. Changes in soil organic carbon

Powlson *et al.* (2011b; 2012) collated data from long-term studies in the UK and elsewhere, which measured changes in soil organic carbon (SOC) following straw incorporation into the soil. This information was reviewed, updated and consolidated to provide a comprehensive summary of the published data on the impact of straw incorporation on SOC.

Table 3 summarises the data from studies at five long-term experimental sites on contrasting soil types (6-24% clay) in England where straw had been incorporated for between 6 and 17 years at rates ranging from 4 to 18 t/ha. (Note that some studies report results from the same experimental sites, but which were made after differing numbers of years of straw incorporation; because of the relative paucity of data, this information has been retained in Table 3). Over all the experiments, SOC increased by an average of 44 (±8) kg/ha/yr/t of straw fresh matter applied, with *c.*13% of the

C added in straw retained in the soil. This supports the value of 50 kg/ha/yr/t reported by Powlson *et al.* (2012) and is similar to the 70 kg/ha/yr/t derived by Smith *et al.* (1997). The range of values reflects the range of experimental conditions, especially soil type. However, there were not enough data to make a distinction in the rate of SOC increase or the percentage of C retained between different soil types, with only one site (Rothamsted) providing data for 'heavy' soil.

Data from 10 non-UK studies where straw was incorporated into the soil at rates ranging from 2 to 12 t/ha/yr for between 6 and 56 years are given in Table 4. These studies had an average rate of SOC increase of 53 (±23) kg/ha/yr/t, which is very similar to the rate of 50 kg/ha/yr/t for the UK studies, although the results are more variable. An average of *c.*17% (±7%) of the C added in straw was retained in the soil, again similar to the *c*.13% for the UK studies. Most of the data were from cool temperate climates growing similar arable crops to the UK and thus provide good corroboration for the rate of SOC increase derived from UK data, although again there was not enough data to distinguish different rates of SOC increase for different soil types.

From a slightly different perspective, Lemke *et al.* (2010) recently reported on a 50 year field experiment to determine the influence of *removing c.*22% of the above-ground wheat residue each crop year on SOC in the top 15 cm of a fallow/wheat/wheat rotation. The study was conducted from 1958 to 2007 on a clay soil in Saskatchewan, Canada and complements results from the same site listed in Table 4 (Lafond *et al.*, 2009). SOM models were also used to predict the effects of the treatments on soil C change over time, and to estimate likely SOC change if 50% or 95% of above-ground residues were removed each crop year. Crop residue removal reduced cumulative C inputs from straw and roots over the 50-yr experiment by only 13%, and this did not significantly reduce measured SOC concentrations. However, the *simulated* effect of removing 50% of the above-ground residues (compared with the *measured* 22% removal) suggested that there was likely to be a detectable effect on SOC, with 95% residue removal almost certainly affecting SOC. Lafond *et al.* (2009) concluded that although it appeared that a modest amount of residue may be 'safely' removed from these soils without a measurable effect on SOC, this would only be feasible if accompanied by appropriate fertility management. These conclusions support those of Powlson *et al.* (2011b) who cautioned against the annual removal of straw, suggesting this would lead to lowering of SOC and consequently to a deterioration in soil physical properties.

Although it was not possible to distinguish soil type effects from the data in Tables 3 and 4, the degree of organic matter stabilisation and hence SOC accumulation is affected by soil type, with soil aggregation, an important mechanism by which organic matter is protected from decomposition (Lutzow *et al.,* 2006). Hence, clay and loamy soils have a greater capacity to retain C due to the occlusion of organic matter within soil aggregates and clay microstructures as well as by the binding of organic matter to mineral surfaces (Hassink, 1997; Lutzow *et al.,* 2006).

From the evidence summarised above, it is clear that there is a trend for SOC levels to be increased by straw incorporation to arable soils (and depleted by straw removal), albeit by a small amount. Using the updated data from Table 3, and an average experimental straw application rate of 7.5 t/ha[1] (Powlson *et al.,* 2011), *c*.330 kg/ha C could be retained in the topsoil, equating to 0.36% of the typical C content of an arable soil in England and Wales (*c.*91 t/ha, assuming 28 g/kg SOC, 1.3 g/cm^3 bulk density and 25 cm soil depth, Webb *et al.,* 2001). These estimates are lower than the annual rate of *c.*500 kg/ha/yr observed over 8 years of straw incorporation (*c.*7.5 t/ha/yr) at an experiment in Ireland under similar climatic conditions (van Groenigen *et al*., 2011). Moreover, using current average GB straw yields (3.4 t/ha; Table A2), the amount of C returned to the topsoil is likely to be lower still at *c*.150 kg/ha/yr for winter wheat and *c.*80 kg/ha/yr for OSR straw, equating to 0.16% and 0.09% of topsoil C. This compares with a typical application of FYM, biosolids or green compost (at rates equivalent to 250 kgN/ha) which have been shown to increase topsoil SOC by 630, 1500 and 1400 kg/ha/yr, respectively (Powlson *et al.,* 2012).

[1] Experiments usually use whole crop straw yields (i.e. to ground level). In older experiments, straw stem lengths may have been longer than modern varieties leading to straw yields somewhat higher than the GB average of 3.4 t/ha for removable wheat straw (see Table A2). Also, in some cases additional straw was applied to plots to establish differential rates of straw.

Table 3. Changes in topsoil organic carbon (SOC) following the incorporation of cereal straw – summary of studies in England.

Site name (Location)	Soil type (clay content)	Cropping	Treatment/ cultivation	Years straw applied	Rate of straw application (t/ha/yr fw)[a]	SOC change (kg/ha/yr/t fw applied[b])	% applied C retained in the soil	Reference
Gleadthorpe	Loamy sand	Arable	Tine+plough[c]	9	10	56	14	Nicholson *et al.*, 1997
(Nottinghamshire)	(6%)	rotation	Plough[d]	9	10	30	8	
			Tine+plough[c]	12	9	4	1	Silgram & Chambers, 2002
Morley	Sandy loam	Arable	Tine+plough[c]	7	7	-8	-2	Nicholson *et al.*, 1997
(Norfolk)	(11%)	rotation	Plough[d]	7	7	-8	-2	
			Tine+plough[c]	10	7	90	22	Silgram & Chambers, 2002
Woburn	Sandy loam	Wheat (osr	Plough[e]	11	18	22	7	Glendining *et al*, 1994; 2005
(Bedfordshire)	(13%)	in 1992)	Plough[e]	11	9	27	8	
			Plough[e]	17	4	92	29	Johnston *et al*., 2009
			Tine[f]	17	4	23	7	
Rothamsted	Silty clay	Wheat (osr	Plough[e]	7	18	58	18	Smith *et al*., 1997
(Hertfordshire)	loam	in 1992)	Plough[e]	7	9	46	14	
	(20%)		Plough[e]	7	4.5	127	40	
			Plough[e]	11	18	39	12	Glendining *et al*, 1994; 2005
			Plough[e]	11	9	58	18	
			Plough[e]	17	4	6	2	Johnston *et al*., 2009
			Tine[f]	17	4	69	22	
Seale-Hayne	Silt loam	Winter	Chisel plough	13	8.0	6	2	Hazarika *et al*., 2009
(Devon)	(11%)	wheat	Mouldboard plough	13	8.1	93	30	
			No-till	13	8.3	54	17	
Mean (se)						**44 (8)**	**13 (3)**	

[a]Whole crop straw yields (i.e. to ground level);.[b]Difference in SOC between treated (straw incorporation) and un-treated plots per tonne straw fresh weight (fw) applied, assuming 30 cm soil depth and 1.3 g/cm^3 bulk density at all sites. [c]Incorporated by tine to 15cm and autumn ploughed to 30cm. [d]Autumn ploughed to 30cm. [e]Autumn ploughed to 20cm (inversion tillage). [f]Tine cultivation to 10-20cm (non-inversion tillage).
se = standard error;

Table 4. Changes in topsoil organic carbon (SOC) following the incorporation of cereal straw – summary of non-UK studies.

Site name (Country)	Soil type (clay content)	Cropping	Treatment/ cultivation	Years straw applied	Rate of straw application (t/ha/yr fw)	SOC change (kg/ha/yr/t fw applied[b])	% applied C retained in the soil	Reference
Queensland (Australia)	Vertisol (41%)	Sorghum	Tine	6	4	146	46	Saffigna *et al*., 1989
Queensland (Australia)	Vertisol (41%)		No till	6	4	163	51	
Star City (Canada)	Gray luvisol	Barley/pea	Straw	8	3.5	-167	-52	Malhi & Lemke, 2007
Aslov (Denmark)	Sandy loam (11%)	Barley	Straw	10	12	107	34	Thomsen, 1993
Ronhave (Denmark)	Sandy loam (14%)	Barley	Straw	18	4	33	10	Powlson *et al*., 1987
Studsgaard (Denmark)	Loamy sand (6%)	Barley	Straw	18	4	60	19	Powlson *et al*., 1987
36 Parcelles (France)	Agrudalf loam	Bare fallow	Straw	26	7	77	24	Houot *et al*., 1989
Ultana (Sweden)	No data	Arable	Straw	26	8.7	66	21	Persson & Mattson, 1988
Gembloux (Belgium)	(15%)	Arable	Straw	30	2.4	65	20	Frankinet & Raimond, 1996; Smith *et al*., 1997
Indian Head (Canada)	Black chernozem	Fallow/wheat/ wheat	Straw	50	3	-5	-2	Lafond *et al*., 2009
Pendleton (Oregon)	Silt loam	Wheat/fallow	Straw	56	5	11	4	Rasmussen & Parton, 1994
Carlow, Ireland	Haplic luvisol sandy loam	Wheat	Straw+CT	8	7.4	71	22	Van Groenigen *et al.*, 2011
Carlow, Ireland	Haplic luvisol sandy loam		Straw+RT	8	7.6	67	21	
Mean (SE)						**53 (23)**	**17 (7)**	

[a]Data from a number of other non-UK studies which were included in the review by Powlson *et al*. (2011) (e.g. Dalal *et al.*, 1991) or were published at a later date (e.g. Sommer *et al*., 2011), could not be included in Table 4 because not all the necessary data were reported (e.g. SOC concentrations, straw addition rates etc.). It may be possible to obtain information from the 'Ultuna' long-term soil organic matter experiment in Sweden (Kirchmann *et al.*., 1994, Karhu *et al.*, 2012) where straw (and other organic materials) was applied from 1956 to 1991. However, this appears to have been published as a thesis from the University of Agricultural Science, Uppsala, Sweden and it was not possible to obtain a copy in the timescale of this project.
[b]Difference in SOC between treated (straw incorporation) and un-treated plots per tonne straw fresh weight (fw) applied, assuming 30 cm soil depth and 1.3 g/cm^3 bulk density at all sites.
SE = standard error.

Annual rates of SOC accumulation change over time. After a change of management (such as the start of regular organic material applications, zero tillage etc.), SOC content tends to move towards a new equilibrium value characteristic of the soil type, land use and climate. Consequently, the annual rate of SOC increase declines over time as the new equilibrium value is approached. So, inevitably (all other factors being equal), the annual rate of SOC increase obtained from a long-running experiment is less than from a newly established experiment. A consequence of this ‘diminishing return’ situation is that, whatever annual rate of SOC increase is used, it must not be assumed that it continues indefinitely. Eventually (e.g. after a period of 100 years or a little more in temperate climates) the annual rate of SOC increase will be zero. This is demonstrated quite clearly by the changes in SOC measured on the Broadbalk continuous wheat experiment at Rothamsted (Figure 1). Here SOC is seen to increase with the annual application of FYM, compared with treatments which received no inputs or just inorganic NPK. The greatest rate of increase occurred within the first *c.*50 years, with *c.*50% of the long-term (*c.*100 years) SOC accumulation occurring in the first 20 years. The estimated SOC accumulation rates following straw incorporation given above and in Table 3 and 4 should therefore only be regarded as the *initial* rate of increase (up to *c.*20 years). They are also dependent on straw incorporation being continued indefinitely. Carbon accumulation is reversible, if applications cease, SOC levels will decrease again.

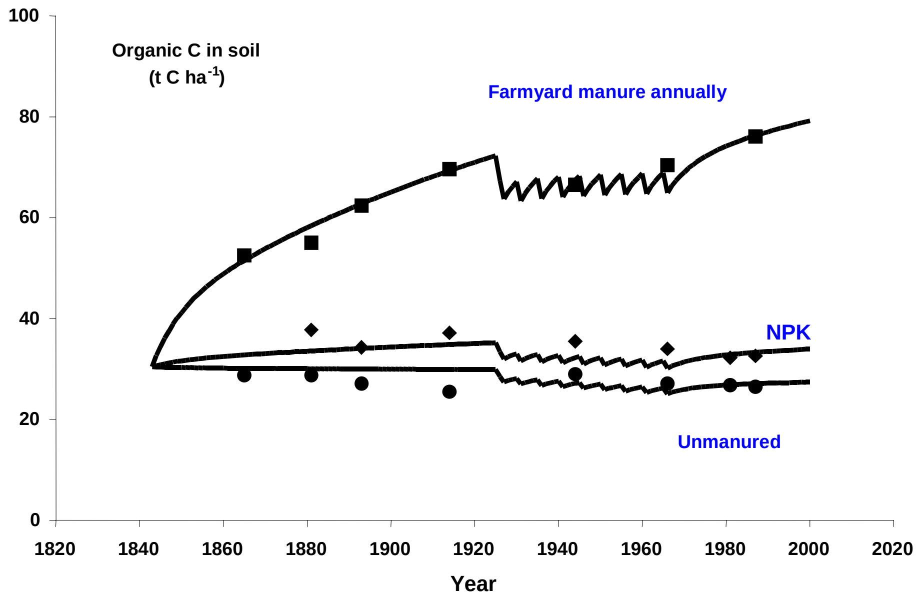

Figure 1. Changes in SOC on the Broadbalk continuous wheat experiment, Rothamsted (data modelled using RothC _26.3: solid lines); data courtesy of Powlson *et al.* (2012).

3.2.2. Soil organic matter implications for the balance of GHG emissions

Increased attention has been placed on soil C storage for climate change mitigation (e.g. Smith *et al.,* 2008; Fitton *et al.*, 2011), with the incorporation of organic materials, including cereal straw, seen as a potential mechanism for increasing soil C storage or 'sequestration'. Table 5 shows the CO_2-C 'savings' that could be achieved through soil C storage on an annual basis by incorporating all the straw produced in Great Britain (see Table A2) and assuming an SOC accumulation rate of 44 kg/ha/yr/t straw applied (see Section 5.2.1).

Table 5. Potential CO_2-C 'savings' following incorporation of all removable cereal straw produced in UK

Crop	2012 Area (ha)	5 year average straw yield (t/ha)	Straw production (Mt)	CO_2-C 'saving' if incorporated (kt)*
Wheat	1,950,000	3.4	6.6	292
Winter barley	380,000	2.8	1.1	47
Spring barley	600,000	2.5	1.5	66
Oats	120,000	3	0.4	16
Oilseed rape	650,000	1.8	1.2	51
TOTAL			10.7	472

*Assuming an annual accumulation rate of 44 kg/ha/y/t straw incorporated.

The potential CO_2-C savings in Table 5 (472 kt CO_2-C) are approximately half those estimated by Smith *et al.* (2000b) who reported a mitigation potential of 880 to 930 kt CO_2-C, despite assuming the incorporation of only an extra 5.3 Mt straw (compared with 10.7 Mt in Table A2) and an annual C accumulation rate of 1.31%/yr.

However, in order to determine the overall effect of straw additions on the balance of GHG emissions, potential decreases/increases due to changes in fertiliser N use and other indirect sources of CO_2 (e.g. fuel consumption) should be taken into account. It is also questionable, whether increases in SOC or CO_2-C savings following straw incorporation can be counted as genuine additional C storage (against a present day baseline). Powlson *et al.* (2007, 2012) stressed that it was essential to consider the alternative fate of the straw (or other organic material) if not incorporated into the soil. About 50% of annual straw production is already returned to the soil, with the vast majority (*c*.47%) of the remainder returned in the form of FYM (Stoddart & Watts, 2012). About 0.3 Mt (*c*.2%) is currently used for electricity generation, which is set to increase to *c*.0.75 Mt (*c*.6%) following the building of a further three power stations.

Consequently, there is little scope for additional straw to be used to increase SOC stocks for the mitigation of climate change. Indeed, Powlson *et al.* (2007) suggested that adding certain organic materials (straw/cattle slurry) to soil was generally an inefficient way of mitigating climate change and that their use to generate bioenergy (e.g. through biomass burning or the anaerobic digestion of slurries) achieved greater CO_2-C savings. For example, cereal straw combustion to generate electricity was calculated to provide annual CO_2-C savings (through displacement of electricity generated from coal) that were 7-10 times greater than those achievable through soil incorporation (taking average annual SOC accumulation rates in arable soil over a 100 year timescale; Powlson *et al.,* 2007). Stoddart & Watts (2012) suggested similar differences, reporting that soil incorporation could fix 733 kg CO_2/ha/yr, as opposed to electricity generation which could save 5000 kg CO_2 compared with coal. Our updated figures suggest even more benefit from electricity generation, with the SOC accumulation rate of 44 kg/ha/yr/t resulting in a return of 150 kg/ha C with straw from a typical winter wheat crop (550 kg/ha CO_2 equivalents).

3.3. Soil physical properties

3.3.1. Effects of straw incorporation on soil physical properties

Increases in SOM from straw incorporation and organic material additions have been associated with changes in soil physical properties and nutrient status (Bhogal *et al*. 2009), as well as impacting on the soil microbial biomass, which in turn influences soil stability and nutrient cycling (Powlson *et al*. 2011b). There is a very limited UK evidence base, so most researchers have looked elsewhere for data to quantify these impacts. For example, Bhogal *et al*. (2009) reviewed two non-UK studies where the return of OC in crop residues was reported to increase soil aggregation, porosity, infiltration and water holding capacity (Munkholm *et al*., 2002; Schjonning *et al*, 1994;). A later review (Powlson *et al*., 2011) summarised the results of several other non-UK studies (Biederbeck *et al*. 1980; Ketcheson & Beauchamp, 1978; Malhi and Lemke, 2007) where repeated straw additions increased aggregate size and stability, which could be beneficial for seedling emergence and root growth and could decrease soil erosion risk, although these benefits were not quantified. In contrast, Nuttall *et al* (1986) reported no effect of straw incorporation on soil aggregation or soil moisture measured seven years later at one of the same sites, indicating that beneficial effects may be transitory. Notably, most of these studies were performed at single sites and there was no evidence to suggest how soil type might influence the magnitude of the soil physical property changes observed.

Johnston *et al.* (2009) briefly discussed how the long-term experiments at Rothamsted have been used to measure the effects of SOM on various aspects of soil structure e.g. soil friability, soil aggregation, aggregate stability and water infiltration. In one such study, Watts *et al.* (2006) measured the draught (i.e. the force per cross-sectional area of worked soil) required for inversion ploughing to 23 cm on the Broadbalk experiment which had received differential manure and N fertiliser rates for 157 years (clay loam/silty clay loam soil). Although the largest differences in draught were related to clay content (which ranged from 19 to 39% clay) there was a decrease in draught of up to 12% on plots that had received more than 96 kg N/ha (i.e. where more OC had been returned to the soil with crop residues). In contrast, Bhogal *et al*. (2011) found no difference in plough resistance on a sandy clay loam at Ropsley (27% clay) and a sandy soil at Gleadthorpe (5% clay) which had received differential crop residue inputs for 17 to 23 years, perhaps indicating the very long time periods required for changes in soil physical properties to manifest themselves.

Since these reviews first appeared, a limited number of additional studies have been published on the impact of straw (or other crop residue) additions on soil physical properties. This wide-ranging (both in terms of geographic location and experimental timescale) and sometimes contradictory data has been summarised in Table 6.

In the UK, Hazarika *et al.* (2009) reported results from a long-term field experiment established in 1982 at Seal-Hayne in Devon to assess the impact of contrasting tillage (no-till, chisel plough and mouldboard plough) on winter wheat agronomy. In 1993, an additional treatment was imposed whereby straw was either incorporated or removed. After 13 years, straw incorporation caused a 2.3-5.0% decrease in soil bulk density at depths of 10-20 cm and 20-30 cm, suggesting that this silt-loam soil (11% clay) was less prone to compaction than when straw had been removed. In a mesocosm experiment, Al-Maliki & Scullion (2013) assessed how earthworms and residue incorporation (grass-clover hay or wheat straw) affected aggregate stability on a Welsh arable soil (26% clay). In the absence of earthworms, straw was more effective than hay in promoting stability (an increase of 21% for straw versus 13% for hay compared to no residue return).

In Iran, Karami *et al*. (2012) applied different types and rates of organic materials (including wheat straw) for three consecutive years. On plots receiving wheat straw, the proportion of water stable aggregates (>0.5 mm) was higher than on the control treatment, although this was not statistically significant. The authors reported that wheat straw additions decreased soil bulk density and increased infiltration rates compared to the control treatment, but neither of these changes was statistically significant. Lenka & Lal (2013) reported on a 15 year field study on a silt loam soil in Ohio where wheat straw was applied at 0, 8 and 16 t/ha/yr. In comparison to the control, the SOC concentration in the top 10 cm of soil increased by 32% and 90% on the 8 and 16 t/ha/yr straw treatments, respectively, with a corresponding increase in the SOC stock of 21-25% and 50-60%, respectively. The proportion of water stable aggregates (>250 mm) increased by 1.4-1.8 times and of micro-aggregates (53-250 mm) by 1.4 times, with increasing rates of straw addition. In contrast, Limon-Ortgea *et al*. (2008) found only ‘minimal’ effects of straw management on aggregate size distribution from a study initiated in 1998 in northwest Mexico.

The evidence in Table 6 and discussed above suggests that the incorporation of crop residues (and associated OC returns) can influence soil physical properties; in particular aggregate size and aggregate stability tended to increase, while bulk density decreased following straw incorporation. Such improvements in soil physical condition are likely to result in improved workability and greater resilience to soil erosion and compaction. Improvements were seen after anything between 1 and 157 years of annual straw incorporation, with the single year effect only seen in a mesocosm experiment and the majority of improvements only seen after at least 8 years of incorporation in the field. The studies do not report how the straw is removed and whether the operation resulted in increased trafficking across the experimental plots, which would be likely to exacerbate any deterioration in soil physical condition. Notably, most of the studies also focussed on a single site, with a limited set of soil properties measured. Overall, there was a lack of data quantifying the relationships between crop residue C returns and changes in soil physical properties, and very little information on how these relationships might vary with soil type.

Table 6. Summary of experiments measuring changes in soil physical properties resulting from straw/crop residue incorporation.

Soil physical property measured	Years straw returned	Country (site name)	Soil type (%clay)*	Crop	Observed change	Source
Aggregate stability	1	UK (Wales)	(26%)	Wheat	↑ (21% increase)	Al-Maliki & Scullion, 2013
Aggregate stability	17-23	UK (three sites)	scl/ls/sl	AR	-	Bhogal *et al.*, 2009
Aggregate size distribution	7	Mexico	-	Wheat	- (minimal effect)	Limon-Ortega *et al.*, 2008
Aggregates (>38 mm)	8	Canada (Star City)	Gray luvisol	AR	↑ (68% increase)	Malhi & Lemke, 2007
Aggregates (<0.83 mm)	8	Canada (Star City)	Gray luvisol	AR	↓ (35% decrease)	
Aggregates (1-20 mm)	10	Denmark	sl	Barley	-	Christensen, 1986
Aggregates (1-20 mm)	17	Denmark	ls	Barley	↑ (	
WSA	3	Iran	-	Wheat	↑ (ns)	Karami *et al.*, 2012
WSA (>250 mm)	15	USA (Ohio)	zl	Wheat	↑ (1.4-1.8 times)	Lenka & Lal 2013
WSA (53-250 mm)	15	USA (Ohio)	zl	Wheat	↑ (1.4 times)	
Aggregate MWD	8	Canada (Star City)	Gray luvisol	AR	↑ (25% increase)	Malhi & Lemke, 2007
Aggregate MWD	19	Canada (Melfort)	Black chernozem	Wheat	↑ (8% increase)	Biederbeck *et al.*, 1980
Aggregate MWD	20	Canada (Indian Head)	Black chernozem	Wheat	↑ (40% increase)	
Aggregation	26	Canada (Melfort)	Black chernozem	Wheat	-	Nuttall *et al.*, 1986
Aggregate strength (dry soil)	100	Denmark (Askov)	sl	AR	↓	Munkhom *et al.*, 2002
Bulk density	3	Iran	-	Wheat	↓ (ns)	Karami *et al.*, 2012
Bulk density	13	UK (Seal Hayne)	zl (11%)	Winter wheat	↓ (2.3-5.0% decrease	Hazarika *et al.*, 2009
Bulk density	17-23	UK (three sites)	scl/ls/sl	AR	-	Bhogal *et al.*, 2009
Bulk density	90	Denmark (Askov)	sl	AR	↓ (3% decrease)	Schjonning *et al.*, 1994
Shear strength	90	Denmark (Askov)	sl	AR	-	Schjonning *et al.*, 1994

Soil physical property measured	Years straw returned	Country (site name)	Soil type (%clay)*	Crop	Observed change	Source
Shear strength	100	Denmark (Askov)	sl	AR	↑ (ns)	Munkhom *et al.*, 2002
Shear strength	17-23	UK (three sites)	scl/ls/sl	AR	↓ (decreased with increased C input)	Bhogal *et al.*, 2009
Penetrometer resistance	90	Denmark (Askov)	sl	AR	**-**	Schjonning *et al.*, 1994
Porosity	17-23	UK (three sites)	scl/ls/sl	AR	**-**	Bhogal *et al.*, 2009
Porosity	90	Denmark (Askov)	sl	AR	↑ (5% increase)	Schjonning *et a*l., 1994
Moisture content	26	Canada (Melfort)	Black chernozem	Wheat	**-**	Nuttall *et al.*, 1986
Moisture content	90	Denmark (Askov)	sl	AR	↑ (7% increase)	Schjonning *et al.*, 1994
Specific draught	17-23	UK (two sites)	scl/ls	AR	**-**	Bhogal *et al.*, 2009
Specific draught	157	UK (Rothamsted)	cl	Wheat	↓ (12% decrease)	Watts *et al.*, 2006
Available water capacity	17-23	UK (three sites)	scl/ls	AR	**-**	Bhogal *et al.*, 2009
Infiltration rate	3	Iran	-	Wheat	↑ (ns)	Karami *et al.*, 2012

↑ Soil property increased; ↓ Soil property decreased**; -** Soil property unchanged
*sl, sandy loam; ls, loamy sand; zl, silt loam; scl, sandy clay loam; cl, clay loam
AR, Arable rotation
MWD, Mean weight diameter (the average size of soil aggregates)
WSA, Water stable aggregates
ns, not significant

3.3.2. Valuing the benefits of changes in SOM and soil properties

Quantifying the financial value of SOM (and associated improvements in soil quality) to a farming system and determining the ‘critical’ level of SOM below which soil functioning becomes impaired continues to challenge soil scientists (e.g. Loveland & Webb, 2003). Improvements in soil physical condition (structure and bulk density) are likely to improve workability, reduce compaction and erosion and encourage infiltration; factors which should result in lower fuel costs (ease of cultivation) and higher yields (improved establishment, rooting, water and nutrient supply). However, this has proved very difficult to quantify, given the relatively small and somewhat variable changes observed, the timescales involved and background ‘noise’ (e.g. high background SOM content, annual variation in yields and weather conditions). Indeed, current research at Rothamsted under HGCA project RD-2012-3787 (Improvement of soil structure and crop yield by adding organic matter to soil), aims to study the effect of organic matter additions on yield and in particular to quantify the minimum addition of external sources of organic matter (including straw) to bring about the maximum improvement in crop yield. This project only started in 2012 and the results are not yet available.

There have been few attempts to quantify the financial value of SOM increases and associated improvements in soil physical condition. Watts *et al.,* (2006) measured a decrease in plough draft force following long-term (>100 years) straw incorporation on the Broadbalk field experiment that was equivalent to a 12% saving in tillage energy, or 6 MJ/ha. This equates to a saving of 0.2 l/ha of diesel fuel assuming an energy content of 36 MJ/l. At current red diesel prices (£0.70/l) this amounts to a saving of just 14 p/ha. As discussed above, however, Bhogal *et al.* (2011) were not able to detect any changes in draught force following *c.*20 years straw incorporation.

Bhogal *et al.* (2009, 2011) attempted to relate SOM inputs with measured changes in a range of soil physical properties. The effects of OC additions from farm manures and crop residues (i.e. straw) on selected soil physical properties were studied at 7 sites with a range of soil types. Whilst repeated (>7 years) and relatively large OC inputs were needed to produce measureable changes in soil properties, they were able to derive relationships between total soil C inputs and available water capacity (AWC), porosity, bulk density (BD) and shear strength, and estimate the financial value of the increases in AWC. However, these soil properties were only influenced by livestock manure OC inputs and not straw returns, therefore it was not possible to put a financial value on the straw OC in the same way.

Nevertheless, anecdotal evidence from farmers and growers suggests that switching to straw incorporation results in yield benefits of more than 0.25 t/ha for wheat, worth around £40/ha at current prices. The yield increases are however only likely to be realised after several years of straw incorporation, so on an annualised basis the benefit would only be *c.*£10/ha. Where straw has been routinely incorporated for the past 10-20 years it is unlikely that occasional straw removal would have a noticeable impact on SOM, soil characteristics or yields in the short term. Where FYM or other organic materials are routinely applied to soils on a rotational basis, then straw incorporation is unlikely to have a noticeable additional impact on SOM levels.

3.4. Soil compaction

Tractors, balers, loaders and trailers used for straw removal are all additional traffic on the soil, with variable damage through soil compaction. Trailers which are loaded on the field can now weigh up to 25 t which would cause significant compaction in the top 30 cm soil horizon .The amount of damage depends on soil wetness, soil type (compaction risks are greater on clay soils), existing soil structure, the weight and type of tyres on the machinery used, and the extent to which the soil has been trafficked.

The use of bale collectors can reduce the area trafficked, eliminating the need for a loader vehicle. Damage can also be minimised by keeping the straw trailer on tramlines as much as possible. However, the view of many farmers would be that those carting straw often have little concern for the damage done to the soil. In a wet season, the risk of increased damage from compaction together with the risk of delayed cultivations means there may be reluctance to bale. The decision will depend on soil type and the ability to travel shortly after rain. If compaction does result from straw removal then the cost to remedy this damage by subsoiling is substantial (*c.*£55/ha) and only possible in season if the soil dries sufficiently and there is time (or a contractor) available. In practice such damage would normally be removed the following year, if at all.

The impact of compaction on yields is difficult to quantify, being dependent on the season and the soil type. Compaction impedes drainage making the soil surface wetter, leading to water-logging in wet years, and also impedes rooting, worsening the drought impact in dry years. Assuming that straw removal caused compaction to 15% of the field area and led to a 30% reduction in yield on these areas, the impact would be a 0.36 t/ha reduction in an 8 t/ha wheat yield across the field, worth £54/ha (based on a grain price of £150/t).

3.5. Summary and conclusions

Soil nutrients

- Straw incorporation can add 40 to 70 kg total N/ha/yr to the soil (based on a cereal crop yielding 7-12 t/ha of grain). This can be mineralised to plant available N forms, however, microbial degradation processes can also lead to N immobilisation.
- Long-term straw incorporation can increase soil N reserves by *c*.7%, but this has not been shown to affect fertiliser N requirements. Application of additional N to offset N

immobilisation in autumn or the reduction of spring N fertiliser in response to straw organic N mineralisation is not generally recommended.

- Straw incorporation returns significant amounts of potash (and some phosphate, Mg and S) to the soil, with fertiliser replacement values ranging from £16/ha (OSR straw) to £53/ha (oat straw). On clay soils which release potash, it is not appropriate to value the K in incorporated straw.
- Providing soils already contain sufficient P and K (i.e. soil Index 3 or above), greater returns could be achieved by selling the straw, and purchasing back the nutrients in the future if required.
- Straw incorporation can reduce over-winter nitrate leaching and P losses to surface waters. The effect of crop residue incorporation on N_2O emissions is currently being investigated as part of a LINK-funded study.

Soil organic matter and carbon storage

- SOM levels can be increased by straw incorporation to arable soils (and depleted by straw removal). Applications of 3.4 t/ha of wheat straw and 1.8 t/ha OSR straw could retain an estimated 150 kg/ha and 80 kg/ha of C in the topsoil, respectively, equating to <0.2% of the typical C content of an arable soil in England and Wales. In comparison, typical FYM, biosolids or green compost applications could increase topsoil SOC by 630, 1500 and 1400 kg/ha, respectively.
- In theory, SOC accumulation and retention is likely to be greater in clay soils than in light, sandy soils, although there was insufficient experimental data to support this hypothesis.
- If all cereal straw in Great Britain was soil incorporated, CO_2-e savings of 472 kt (or 1730 kt CO_2-e) could be achieved; however, as a large proportion is already incorporated (as straw or FYM), it is questionable whether this would be genuine additional C storage.
- Cereal straw combustion is likely to lead to greater CO_2-e savings than the additional soil C storage from straw incorporation.
- Maintaining or increasing SOM should be an important objective for all growers. The importance of straw incorporation in meeting this objective will differ from farm to farm. Where straw has been removed for decades with no other additions of organic materials, then switching to straw incorporation could improve SOM levels in the medium term.

Soil physical properties

- Soil physical condition will improve following straw incorporation, but only after at least 8 years of repeated additions. It is questionable whether annual straw incorporation supplies sufficient OM over the medium term (<10 years) to result in measurable changes in soil physical condition.

- Whilst the value of increased SOM is generally considered to be greater in lighter soils (because starting SOM levels are low and benefits from increased OC are greater), the impact of straw incorporation on SOM levels is likely to be less on lighter soils as the added organic matter is broken down more quickly.
- For a single year on any soil type, the economic value of straw incorporation on soil properties affecting workability or yield is very low in relation to straw prices (i.e. <£5ha).
- Periodic applications (at recommended rates) of bulky organic materials such as FYM, poultry manure, biosolids and composts supply larger quantities of organic matter than cereal straw and are a more effective way of maintaining or increasing SOM levels.

Soil compaction and workability

- Straw baling and removal requires significant additional machinery travel, adding to the risk of soil compaction; if left untreated, this will reduce future crop yields.
- The effect of compaction on yield is rarely noticed, although it can be significant in some conditions. The cost to remedy compaction damage by subsoiling is substantial (*c.*£55/ha). Compaction can also impact the wider environment through less infiltration leading to more run-off and hence greater sediment and nutrient losses.
- Chopping straw prior to incorporation can result in layers of compressed material at the soil surface which does not decompose (especially in heavy clay soils) affecting the growth of following crops. Moreover, ploughing in straw residues without mixing into soil can leave a persistent straw barrier through which roots cannot penetrate.

4. Agronomic impacts

Straw management has a range of positive and negative effects on weed, pest and disease severity, as well as effects on crop establishment which are not linked to pests or diseases. The overall impact of straw management on yield depends on the weed, pest and disease pressures on a crop as well as soil factors described in Section 5.

4.1. Weeds

Straw management can influence weed control through the return of weed seeds, allelopathic effects, and the effectiveness of residual herbicides. Also, the contamination of straw by herbicides has implications for its end-use, as some herbicide residues can be a potential hazard to subsequent crops. Indeed, certain herbicides (e.g. HRAC group O Pyridine carboxylic acid family) specifically preclude some end uses for straw, for example as horticultural mulches, and/or prescribe the incorporation of straw in the following crop.

4.1.1. Herbicide residues on straw

A limited number of herbicides have label restrictions associated with the use of straw from treated crops (Table 7). They are all members of the pyridine carboxylic acid group which are absorbed rapidly by roots and leaves and translocated within the plant.

Table 7. Herbicides that may be present in straw, their herbicide group and chemical family. (PPDB, 2013; product labels)

Herbicide group (HRAC)	Chemical family	Related herbicides	Label restriction for straw
O	Pyridine carboxylic acid	aminopyralid	Yes
		clopyralid	Yes
		fluroxypyr	Yes (high rate only)
		picloram	Yes

Aminopyralid is available in mixtures with propyzamide for use in OSR (CRD, 2013); there are no products registered for use in cereals which contain aminopyralid. A stewardship programme has been devised by Dow AgroSciences to cover all products containing aminopyralid (www.dowagro.com). Where aminopyralid has been applied, straw must not be removed from the field and must not be fed to animals or used as bedding. All remains of the OSR crop should have completely decayed before planting susceptible crops.

Labels of products containing clopyralid alone or in mixture contain restrictions on using treated crops for composting or mulching, and manure from animals fed on treated crops. The straw remaining in the field can also have an effect on following crops and should be fully decayed before planting susceptible crops. Picloram is only available in mixture with clopyralid (CRD, 2013) for use in OSR and has similar label restrictions to clopyralid alone.

Label restrictions for products containing fluroxypyr relate to the higher rate (2.0 l/ha) for control of volunteer potatoes in winter wheat and barley. Straw from these treated crops should only be used for animal bedding and manures, and should only be used on or before cereal or grass crops.

4.1.2. Wheat straw and allelopathy

The presence of wheat straw can have allelopathic effects on the following crop and on weeds (Satsangi, 2010; Shilling *et al*., 1985; Steinsiek *et al*., 1982; Wu *et al*., 2001). Wu *et al*. (2001) showed that wheat seedlings were able to synthesize and exude allelochemicals including phenolic acids, hydroxamic acids and short-chain fatty acids compounds through their root system, into the surrounding medium. The degree of growth inhibition depended on the residue type, quality, placement, degree of decomposition, microbial activity, nutrient status and other physical parameters (Rice, 1984). Generally in the UK, any effects are transitory and have little effect on following crops.

In a four-year experiment on continuous barley, Boguzas *et al*. (2006) found that after the first two years, straw incorporation reduced weed populations and the weed seed bank, particularly of *Chenopodium album* (fat hen), an effect that could have been due to allelopathy. OSR straw has no recorded allelopathic effects on arable crops in the UK.

4.1.3. The effect of straw on herbicide activity

The presence of straw on the soil surface can affect the activity of residual herbicides by acting as a physical barrier. Pot experiments (Kudsk & Mathiassen, 2006; Kudsk, 2007) showed that 1 t/ha of chopped straw lying on the soil surface reduced the efficacy of flupyrsulfuron and pendimethalin, with a greater reduction with 3 t/ha straw. Improved herbicide formulations (e.g. Stomp Aqua) have been shown to increase wash off, allowing more product to reach the soil (BASF, 2013).

In practice, chopped straw does not usually form a complete blanket over the soil surface and some form of cultivation generally occurs before a crop is established. Most growers do not perceive a decline in herbicide activity due to the presence of straw and do not make changes to their cultivation regimes. Minimum cultivations do increase weed populations, although this is not due to reduced herbicide performance, but to incomplete burial or build-up of weed seeds, particularly grasses, in the cultivation layer of the soil.

4.1.4. Straw as a source of weed seeds

Cereal straw used for mulching often contains shed grain and sometimes whole ears of grain. If the straw is from a weedy crop, weed seeds may also be present. Crop harvest is a critical time for the dispersal of crop and weed seeds. In cereals, it has been estimated that on average 40% of weed seeds have been shed by the time of harvest (Fogelfors, 1982). About 5% of seeds remain below normal stubble height, leaving between 45 and 70% of weed seeds to pass through the combine harvester with the straw. Some of these seeds can become trapped with the straw during baling and transported from the field.

The presence of weed seeds in straw is generally of minor consequence. However, purchasers should be aware of the source of straw, particularly when manures are returned to arable land, to prevent the spread of pernicious weeds such as resistant black-grass.

4.1.5. Straw mulches and weed control

Short-term mulching with cereal straw can be used to manipulate or reduce weed emergence, reduce the risk of soil erosion, reduce pest problems, retain moisture, protect from frosts, raise soil temperatures and reduce nitrate leaching loss. Straw mulches can exclude light and hence enhance germination of some weed species e.g. barren brome (*Anisantha sterilis*), and affect seed persistence in others. For example, Jensen (2009) showed that for most grass weed species, the persistence of seeds on the soil surface was unaffected by covering with chopped straw, but for black-grass *(Alopecurus myosuroides)* straw cover significantly increased persistence.

4.2. Pests

4.2.1. Slugs

Incorporating straw provides a food source for slugs so can result in higher populations, more damage and a greater need for molluscicides. This is especially important in the light of the Water Framework Directive (WFD 2000/60/EC) which commits the European Union member states to achieve good chemical and ecological status of all water bodies by 2015. At present over 90% of farmers apply metaldehyde-based pellets for slug control in preference to products based on other active ingredients. Metaldehyde has been detected in water and water companies have made it clear that unless levels are reduced they will seek restrictions on its use.

Straw management can influence slug populations. At one Oxfordshire site where wheat straw residues were present, ploughing considerably reduced slug numbers, whereas minimum tillage had little effect (HGCA, 1988). Glen *et al* (1984) found that shallow incorporation of wheat straw (5-10 cm) did not reduce slug numbers but did result in a significant reduction in damage to seeds and seedlings compared to plots that were direct-drilled. This was thought to be due to seeds being less accessible to slugs where there had been cultivations.

A long-term experiment carried out on two trial sites (a light-textured soil and a heavy-textured soil) near Carlow in Ireland showed that slug numbers were significantly reduced where wheat straw was incorporated in comparison to removal in two of 15 experiments (Kennedy *et al,* 2013). In the remaining thirteen experiments there was no significant effect of straw management on slug populations. The authors conclude that the absence of slug proliferation due to straw incorporation is of considerable importance to minimum tillage practitioners in Ireland.

Symondson *et al*. (1996) investigated the effect of tillage and OSR straw management on slugs and the carabid predator *Pterostichus melanarius*. They found that predator numbers were reduced by tillage, relative to direct drilling, and increased by straw incorporation, relative to non-inversion tillage. Predator numbers were correlated with slug populations, so straw incorporation also increased slug numbers. There are likely to be interactions between effects of straw incorporation on slug damage and cultivation system used. Compared to non-inversion tillage, ploughing will bury much of the trash so it will be less available to slugs for feeding. On the other hand, some minimum tillage cultivation equipment, such as straw harrows, are now marketed partly on their perceived benefits for slug control. However there is little evidence in the scientific literature on the impact of cultivations and soil conditions on slug populations and damage (Ellis & Berry, 2013).

Direct evidence of the impact of straw incorporation or removal on slug populations, activity and damage is lacking. General evidence of the impact of slug damage on yield is also limited (Ellis & Berry, 2011). Ellis & Berry (2013) investigated the impact of slug damage on yields through simulated defoliation and seed rate studies. Experiments in both wheat and OSR showed that current commercial seed rates are close to optimal, so that slug damage that substantially reduces plant populations will reduce yields in many situations unless seed rates are increased. It also showed that simulated leaf grazing reduced yields in both wheat and oilseed rape,

About 20 to 25% of the wheat crop is treated for slugs every year. Yield losses due to slug damage ranges from zero (where crops recover and compensate) to 100% (where the majority of plants are destroyed and the crop has to be re-drilled). On average it is estimated that without molluscicide treatment, wheat crops would lose 5% of their yield on slug infested land. This is equivalent to approximately 188,000 t of grain or 1.1% of the total wheat production (Clarke *et al*., 2009).

Around 59% of the OSR crop is thought to require slug treatment each year. There is a large range of potential yield loss, with the average loss estimated at 4% where slug-infested land is not treated. This is equivalent to approximately 2.4% of total OSR production (Clarke *et al*., 2009). Slug populations are perceived to be higher in OSR crops than wheat and their propensity to do damage greater, because they can graze the growing point above ground killing the plant, whereas in wheat the growing point remains below ground. However, recent work funded by CRD (Ellis & Berry, 2013) suggests that wheat may be as vulnerable to yield loss from slugs as OSR.

The results of the Oxfordshire study (HGCA, 1988) imply that slug numbers could double each year that wheat straw is incorporated rather than removed, although more data is needed to confirm this estimate. This suggests there may be a strategic long term impact of straw incorporation supporting larger slug populations.

The grey field slug breeds throughout the year with main periods in spring and again in September/October. The time taken for eggs to hatch varies with conditions, but in warm weather this may be within 3 weeks (Gratwick, 1992). Although there is no supporting experimental evidence, it is feasible that straw incorporation in summer/autumn could provide sufficient extra food such that, in the right conditions (i.e. warm & wet), slug populations could increase by around 50% during this period compared with straw removal. Slug damage and yield impacts will depend on the starting slug population, slug activity and the ability of the crop to grow away from the damage, which in turn depends on soil and weather conditions. In most normal situations with low to moderate slug populations, the impact of straw incorporation on slug damage and control is likely to be negligible. However, in extreme cases straw incorporation could be the difference between heavy slug damage and complete crop failure, where the costs of redrilling and reduced yield potential of a later sown crop could be £100s /ha. More likely in situations with high slug populations and conditions conducive to damage, straw incorporation might cause additional damage resulting in a *c.*2% yield loss (£24/ha for wheat for 8t/ha yield at £150/t; £19/ha for OSR for 3.2t/ha yield at £300/t) or perhaps necessitate additional slug pellet applications. The cost of molluscides varies from around £6/ha for the cheapest metaldehyde pellets to over £20/ha for the most expensive methiocarb pellets. Importantly, the total application of metaldehyde pellets is limited to 700g/ha over the season; it is possible that incorporated straw could make the difference between needing only one or two applications of metaldehyde to needing more than is permitted, requiring the use of the more expensive methiocarb pellets.

Whilst straw incorporation can increase slug populations in the medium term, crop damage may be minimal because the partly decomposed straw might be more attractive to slugs as a food source than newly emerging seedlings, although there is no published evidence to support this hypothesis. To suggest that straw be used as a cultural method of limiting slug damage at establishment is controversial, and further research is needed to determine the efficacy of this approach.

4.2.2. Aphids

Two aphid species, the grain aphid (*Sitobion avenae*) and the bird cherry-oat aphid (*Rhopalosiphum padi*) are vectors of barley yellow dwarf virus (BYDV), a potentially serious disease of UK cereal crops. Relatively low populations of BYDV-carrying aphids can cause economic damage as, given favourable warm conditions, the pests can reproduce and spread rapidly within the crop.

Kendall *et al.* (1991) found that BYDV infection was more prevalent in barley following straw baling than straw incorporation. Infection was also increased by tillage, with ploughing leading to worse infection than non-inversion tillage, which in turn was worse than direct drilling. Yield was negatively correlated with BYDV incidence, so straw incorporation raised yield relative to straw baling. Populations of several species of non-specific aphid predators were also negatively correlated with BYDV prevalence, suggesting that tillage and straw disposal may affect virus levels at least in part via effects on predators, rather than only via direct effects on aphids.

Kennedy *et al*. (2010) found inconsistent effects of cultivation (minimum versus conventional tillage) on aphid numbers and BYDV incidence, but the same effects of straw management as Kendall *et al*. (1991) i.e. that straw incorporation usually reduced aphid numbers and BYDV incidence, relative to straw removal.

OSR is susceptible to different aphid species. The peach potato aphid (*Myzus persicae*), can transmit turnip yellows virus (formerly beet western yellow virus), and cabbage aphid (*Brevicoryne brassicae*), can transmit turnip mosaic virus and cauliflower mosaic virus. There is no evidence that these species are affected by straw disposal method.

4.2.3. Other pests

The presence of cereal straw residues has been found to reduce populations of yellow cereal fly and wheat blossom midge (Glen, 2000), although there was no clear explanation of this observation. Both bibionids (e.g. *Bibio marci* the St Marks fly) and bean seed fly (*Delia platura*, *D. florilega*) are minor pests of cereals and known to be encouraged by the presence of organic matter in the soil (Gratwick, 1992); thus straw incorporation could favour these pests.

Wahmhoff *et al*. (1999) showed that cultivation of OSR stubble reduced the hatching rate of rape stem weevil, but also reduced populations of the parasitoids of cabbage stem weevil and pollen beetle. However, they failed to find any effects on pest incidence in following OSR crops.

4.3. Diseases

When evaluating the effects of straw management on crop disease, stubble should be considered separately from the upper parts of the plant that are baled or chopped. Stubble residues will almost invariably be present and these carry pathogens in the dead leaves as well as in the stem bases and roots. The effects of straw incorporation on diseases may be small or variable depending on the inoculum present in the crop above the stubble. This inoculum will often be small in relation to that in the stubble and soil-borne pathogens. Thus cereal straw removal is expected to have a smaller effect on disease inoculum than ploughing or cultivations which remove infected stubble residues from the soil surface. This may not be the case for some OSR diseases which develop strongly on the upper parts of the plant.

The impact of straw residues on disease risk will be influenced by disease severity, location of the straw and pathogen survival on straw in addition to crop (host) and weather factors. In addition to the effects of straw management on disease inoculum, crop residues can act as a substrate for non-pathogenic micro-organisms that may suppress diseases. For example, Jenkyn *et al*. (2004; 2010) have shown that the presence of straw can actually suppress development of eyespot even if the straw was infected.

The potential impacts of straw management have been considered for each pathogen separately with respect to their life cycles and the risks posed to surrounding, succeeding and future crops.

4.3.1. Cereals

Eyespot

Eyespot, caused by *Oculimacula yallundae* and *O. acuformis*, is a common stem-base disease of UK cereals. It causes yield loss by reduction of water and nutrient uptake, leading to whiteheads and lodging. The pathogen overwinters on infected stubble, where it may survive for up to 3 years, and on cereal volunteers and grass weeds. Eyespot is spread short-distances by rain-splash dispersal of conidia or long distances by wind dispersal of ascospores from crop debris.

It would be expected that burial of infected stubble would increase eyespot infections in following crops, but a series of UK experiments has shown that incorporation of crop debris, even if it includes eyespot-infected stem bases, consistently has a disease-suppressive effect (Jenkyn *et al*., 2001, 2010; Prew *et al*., 1995). Eyespot incidence was typically highest with straw burning, and similarly low with straw baling and removal or chopping, followed by cultivations. To confirm that the reduction in eyespot incidence was due to the presence of crop debris, rather than to associated differences in husbandry, Jenkyn *et al*. (2010) applied crop debris from other sites to plots artificially inoculated with eyespot, and found reduced eyespot in straw-treated plots. They suggested microbial antagonism as the most likely mechanism for the disease suppression. A possible alternative or additional mechanism for this effect is silicon (Si) fertilisation by straw residues; Rodgers-Gray & Shaw (2000) have shown that straw incorporation raises Si levels in winter wheat, and that Si fertilisation reduces eyespot infection (Rodgers-Gray & Shaw, 2004).

In a series of four experiments in France, straw burial or removal had no influence on the incidence of eyespot (Colbach & Saur, 1998). In an experiment in western Lithuania, straw removal slightly increased eyespot incidence in winter triticale, relative to straw incorporation, but decreased incidence in spring barley (Janusauskaite & Ciuberkis, 2010). Jenkyn *et al*. (1995) found at one site that straw incorporation reduced eyespot severity in winter barley, relative to straw burning.

Overall the evidence points to straw incorporation reducing incidence of eyespot relative to straw removal. However, in most cases the agronomic impact on yield or fungicide cost is likely to be small and difficult to quantify.

Fusarium

Fusarium spp. and *Microdochium nivale* (formerly known as *F. nivale*) form a disease complex causing foot rot, seedling blight and ear blight in wheat and other cereal crops. The most important infection source is seed from crops with ear infections, but the causal fungi also survive and spread on crop debris in the soil. Seed infection causes damping off, or the development of stem base lesions. Spores can then be splash-dispersed up the canopy to cause ear blight and further seed infection. Yield losses from *Fusarium* infection are usually quite small, but infection can lead to grain mycotoxin production, which can lead to the grain being rejected by buyers due to human and livestock health risks.

In a continuous winter wheat experiment at Rothamsted, Bateman *et al.* (1998) found higher numbers of *F. culmorum* colony forming units (CFUs) in the soil following straw chopping and incorporation than following burning. Straw incorporation by ploughing was found to ‘dilute’ the CFUs through a greater soil depth than incorporation by shallow cultivation. However, in the one season of testing in which severe *Fusarium* disease occurred, severity was higher following straw burning than incorporation. The authors were uncertain whether the CFUs identified were the main inoculum for the disease, or whether straw incorporation also interfered with the infection process, perhaps by production of fungitoxic substances from decomposing straw, or by antagonism or competition from straw-decomposing microorganisms. In the Broadbalk continuous wheat experiment at Rothamsted, Bateman & Coşkun (1995) found no consistent difference in *F. culmorum* propagule numbers between plots with straw removed or chopped and incorporated.

In Australia, Summerell & Burgess (1988) found that burial of wheat stubble residues accelerated decomposition. Survival of *F. graminearum* was correlated with stubble decomposition, with the fungus recovered at very low levels 8 weeks after burial, and not recovered at all after 2 years. Further Australian experiments found that wheat infection by *F. pseudograminearum* (Swan *et al*., 2000) and *F. graminearum* (Wildermuth *et al*., 1997) was more severe when stubble was retained on the soil surface than when stubble was buried or removed. It is not known how well results from an Australian experiment translate to a UK environment as the timescales for stubble decomposition may be very different.

In a series of 5 UK experiments, Rodgers-Gray and Shaw (2000) found that incorporating 10 t/ha straw consistently reduced the severity of diseases including foot rot (*Fusarium* spp.), relative to plots where no straw was incorporated. They suggested that disease suppression by incorporated straw might be due to increased Si availability, as leaf Si was significantly higher in straw-treated plots. However, it should be noted that the amount of straw incorporated in these studies was at least double that typically incorporated in commercial practice. In a 6-year experiment in an irrigated system in the US, there were no consistent differences in inoculum concentrations of *Fusarium* spp. between no-till plots where straw was removed or left standing (Paulitz *et al*., 2010). In a series of 4 French experiments, straw burial or removal had no direct influence on the incidence of foot rot (*M. nivale* and *Fusarium* spp.) (Colbach & Saur, 1998).

There is no direct evidence on the effects of straw management on mycotoxin risk from *Fusarium*, and the effects of straw incorporation on *Fusarium* disease severity, described above, are inconsistent. However, where infected straw or stubble is left in the field, *Fusarium* severity and hence mycotoxin risk should be reduced by incorporating it rather than leaving it on the soil surface (HGCA, 2013; Rodgers-Gray and Shaw, 2000; Summerell & Burgess, 1988; Swan *et al*., 2000).

Sharp eyespot

Sharp eyespot, caused by *Ceratobasidium cereale* (*Rhizoctonia cerealis*), is a common stem disease of wheat and other cereals. The symptoms can sometimes be confused with those of eyespot, but unlike eyespot, it rarely causes significant yield loss. The fungus overwinters as mycelium on infected stubble, as sclerotia, or on volunteers and grass weeds. Young plants are infected by mycelial growth through the soil.

In a series of 4 experiments in France, straw burial or removal had no influence on the incidence of sharp eyespot (Colbach *et al*., 1997a). In UK experiments, straw incorporation caused a slight but significant reduction in sharp eyespot severity, relative to straw burning (Jenkyn *et al*., 1994; Prew *et al*., 1995). As most inoculum will be produced at the stem base, the effects of additional straw incorporation are likely to occur via microbial interactions.

Take-all

Take-all, caused by *Gaeumannomyces graminis*, is a major soil-borne root disease of wheat and barley. The fungus overwinters as mycelium on infected roots and stem bases, volunteers and autumn-sown crops. Primary infection from the soil occurs in the autumn and secondary infection from root to root in the spring and summer. Take-all causes progressive root rotting, leading to yield loss via reduced water and nutrient uptake and premature ripening.

Following the ban on straw burning in 1992, there were concerns that the large and prolonged increase in straw incorporation could increase take-all severity on some soil types. However, at that time there had been very few cases where straw incorporation had been implicated in severe take-all attacks, and in ADAS and Rothamsted experiments, the effects of straw incorporation on take-all had been inconsistent (Hornby, 1998). In a 6-year experiment in an irrigated system in the US, there were no consistent differences in inoculum concentrations of *G. graminis* between no-till plots in which straw was removed or left standing (Paulitz *et al*., 2010). In a series of 4 experiments in France, straw burial or removal had no influence on the incidence of take-all (Colbach *et al*., 1997b). Similarly, a series of UK experiments found that in most crops there was no effect of straw disposal treatment (straw burning, or straw chopping and incorporation by disc/tine or by ploughing) on take-all levels, although in 2 site seasons take-all incidence was higher following shallow straw incorporation than straw burning (Turley *et al*., 2003). In 5-year experiments on continuous wheat, Jenkyn *et al*. (2001) found that at one site that incorporating increasing amounts of straw caused a linear decrease in take-all incidence, but the same pattern was not observed at the other two sites. Averaged across a different series of experiments, Jenkyn *et al*. (1994) found take-all to be slightly more severe following straw incorporation (84.3% incidence) than straw burning (77.3% incidence).

Foliar diseases

Some important foliar diseases of UK cereals overwinter on crop debris, and can be affected by straw and stubble management. These include septoria leaf blotch (*Mycosphaerella graminicola*), rhychosporium leaf blotch (*Rhynchosporium secalis*), net blotch (*Pyrenophora teres*) and powdery mildew (*Blumeria graminis*, formerly known as *Erysiphe graminis*). However, for septoria, most initial infections are via long-distance dispersal of air-borne ascospores, so local residue management is unlikely to have a noticeable effect.

Jordan & Allen (1984) showed that *P. teres* (barley net blotch) conidia were more prevalent above chopped straw left on the soil surface than above stubble, and very low where crop residues were burnt or buried by ploughing. As a result, disease developed more quickly in autumn following direct drilling than following ploughing, and more quickly in the presence of straw or stubble residues than following straw burning. Jenkyn *et al*. (1995) also found that straw on the soil surface increased net blotch (*Pyrenophora teres*) and rhynchosporium severity early in the season but reduced severity in summer, relative to straw burning or burial by ploughing. Kutcher & Malhi (2010) found small and inconsistent effects differences in net blotch severity between straw burning and retention.

In a series of 5 UK experiments, Rodgers-Gray and Shaw (2000) found that incorporating 10 t/ha straw (high compared to the UK average of 3.4t/ha) reduced the severity of septotia leaf blotch, powdery mildew, brown rust (*Puccinia recondita*) and *Fusarium* foot rot, relative to plots where no straw was incorporated. They suggested that the disease suppression by incorporated straw might be due to increased Si availability, as leaf Si was significantly higher in straw-treated plots. Follow-up experiments with pot-grown winter wheat found that incorporated straw or Si fertilisation reduced the severity of mildew and eyespot under high disease pressure, but not always under low disease pressure (Rodgers-Gray & Shaw, 2004). In the same experiments, there were no or inconsistent effects of straw and Si treatments on septoria and brown rust. Survival of *Pyrenophora tritici-repentis*, the pathogen causing tan spot in wheat, is also reduced by stubble incorporation (Summerell & Burgess, 1989).

By contrast, Jenkyn *et al*. (1994) found no effect of straw incorporation on septoria severity, relative to straw burning. In winter barley, net blotch and rhynchosporium leaf blotch severities in autumn were increased when straw was incorporated by non-inversion tillage, relative to burning or incorporation by ploughing, but there were no consistent difference between treatments in spring. In summer, net blotch severity was worst in plots where straw had been burnt.

Jenkyn *et al*. (1994) suggested that the inconsistent effects of straw incorporation on foliar diseases are because the amount of primary inoculum is a relatively minor factor in eventual disease severity. The effects of straw management on overall crop growth and on crop microclimate may be more important factors, at least in some site seasons.

4.3.2. Oilseed rape

Light leaf spot

Light leaf spot, caused by *Pyrenopeziza brassicae*, is an increasingly important leaf and stem disease of OSR and other brassicas, more common in Scotland and the north of England than in the south. Initial infection is via air-borne ascospores produced from the infected residues of previous crops. The disease can affect all the upper parts of the plant so stem residues are an important source of inoculum. The light leaf spot regional forecast uses the severity of light leaf spot on pods to forecast its incidence in the following spring (Welham *et al*., 2004). Burial of infected residues is thought to reduce the infection risk for following crops in nearby fields by reducing the source of inoculum.

At present, average yield loss from light leaf spot is estimated at 10% nationally (P. Gladders, pers. comm.). If straw removal decreases inoculum levels by around 30% and produces a pro rata benefit through decreased incidence and severity, yields could benefit by 3% where there is poor varietal resistance and only partially effective fungicides. This equates to *c*.£30/ha (£20M/annum for the industry) assuming an OSR yield of 3.2t/ha and price of £300/t.

Phoma

Leptosphaeria maculans, the pathogen responsible for phoma canker on OSR, survives on OSR stubble in the period between crops. Airborne ascospores are then released from pseudothecia, and dispersed to infect crops in nearby fields. Early UK studies showed that phoma incidence was correlated to the quantity of crop residues in nearby fields and ploughing decreased disease risk (Gladders & Musa, 1980). Infected stubble therefore represents an infection risk for crops in nearby fields in the next cropping season; burial of straw and stubble can reduce this risk (West *et al*., 2001). Such effects are now more difficult to demonstrate because of the intensity of OSR cropping, and the many sources of air-borne inoculum. Turkington *et al*. (2000) confirmed that burial of OSR residues, compared to leaving them on the surface, speeded up decomposition.

Kutcher & Malhi (2010) found a significant effect of residue management on the incidence of phoma in only 2 out of 9 site seasons. In one, residue burning increased incidence from 12% to 16% relative to residue retention, but in the other, burning reduced incidence from 47% to 38% with conventional tillage and from 47% to 17% with zero tillage. The authors concluded that burning was ineffective in controlling phoma,

Sclerotinia

Sclerotinia is a major stem disease of UK OSR. The pathogen, *Sclerotinia sclerotiorum*, produces sclerotia within infected stems which can survive in soil for over 10 years. Sclerotia germinate in spring to produce apothecia which release air-borne ascospores. Following a severe epidemic, deep burial of sclerotia by ploughing can reduce production of apothecia and spores to infect following crops, but their long survival period means that ploughing in future years may return them to the surface, still active.

Wahmhoff *et al*. (1999) showed that OSR residues decayed more quickly following chopping and shallow soil incorporation and that the burial of residues affected survival of sclerotia and formation of apothecia. However, they failed to detect any effects of tillage practices on sclerotinia incidence in following crops. Kutcher & Malhi (2010) showed in 2 site-seasons in Canada that residue burning increased sclerotinia incidence relative to residue retention. There was no significant effect of residue management in a further 2 site seasons, and the authors concluded that burning did not effectively destroy sclerotia, and may increase infection by reducing impedance of spore movement by crop residues.

Sclerotia can form in all parts of the stem and branches, so straw removal will be more effective if diseased material is present in the upper stem and the straw can be handled carefully so that sclerotia are not shed from weakened or broken stems. Some farmers in southern England have baled rape straw for burning as a disease control measure. If the crop also has light leaf spot and/or verticillium wilt there may be several benefits from straw removal in the short term (e.g. light leaf spot) and longer term (e.g. sclerotina and verticillium).

Yield loss from Sclerotinia can be on average 20% in bad years (and up to 50% in individual fields; P. Gladders pers. comm.). Straw removal could reduce inoculum levels and subsequent yield loss by 50%, worth *c.*£100/ha (£67M for the industry) in a bad disease year, assuming an OSR yield of 3.2t/ha and price of £300/t.

Verticillium

There is little published information on the impact of agronomic practices on verticillium wilt (*Verticillium longisporum*) (Gladders, 2009). Heavily infested plants become grey by harvest as numerous microsclerotia are produced within the in stems and branches. Microsclerotia also form in the roots and stem base, but stem material is likely to be the major source of new microsclerotia. Removal of rape straw would therefore appear to be useful for decreasing the build-up of inoculum in the rotation. This benefit will be quantifiable when suitable soil diagnostic tests are available.

Surveys show that currently only 5% of fields are heavily infested with Verticillium (P. Gladders, pers. comm.) and hence these are at risk of yield loss in perhaps 1 in 4 years. Yield loss may be 10% on average and it is possible that this would be reduced by 50% by straw removal, worth *c.*£50/ha on infected fields, (£420k/annum for the industry), assuming an OSR yield of 3.2t/ha and price of £300/t.

4.4. Crop establishment

Straw left on the soil surface or shallowly incorporated, i.e. above the seed, can impede crop establishment principally due to reduced soil temperature and water soluble toxins from residues or associated micro-organisms (Morris *et al*., 2010). Straw also slows soil drying, but this can be an advantage or a disadvantage, depending on soil and weather conditions.

Morris *et al*. (2009) used container experiments to investigate the effects of wheat straw management on subsequent OSR or sugar beet crops. When straw and seed were either both placed on the soil surface or both shallowly incorporated into the soil, emergence and early growth was reduced by *c*.50%, relative to straw removal. When seed was placed in the soil and straw was left on the surface, emergence was rapid due to good seed-to-soil contact and moisture retention, although straw on the soil surface also reduced day-time soil temperature by an average of 2.5^{o}C.

The impacts of straw incorporation on establishment are closely tied to cultivation and sowing practices. The incorporation of straw may affect the choice of cultivation equipment, or the establishment method may sway the decision of whether straw is removed or not. These issues are discussed further in Section 5, but in general, the impact of straw incorporation on establishment *per se* on farm with modern cultivation equipment is considered to be too small, uncertain and infrequent to be consequential in decision making.

4.5. Yield

The effects of straw management on crop yield are inconsistent: some studies have shown yield benefits of incorporation relative to straw removal, and others yield penalties (Table 8), probably because the yield effects also depend on other factors including soil and weather conditions, nutrient management, and weed, pest and disease pressures. Even in experiments where straw residues reduced crop establishment, there was often compensation such that yield was either unaffected by straw management or increased by residue retention (e.g. Ball & Robertson, 1990; Prew *et al*., 1995; Verhulst *et al*., 2011).

In one long-term UK experiment on a clay soil, yield was one third lower following direct drilling into chopped straw, relative to direct drilling following straw burning, and straw incorporation to 5 cm reduced yield by one fifth, relative to burning (Christian *et al*., 1999). Straw incorporation also reduced yield relative to burning when residues were ploughed in, although the difference was smaller. In three 5-year experiments on continuous wheat, Jenkyn *et al*. (2001) found that straw incorporation (up to 20 t/ha to give best chance of testing effects) reduced first year yield, but had no significant effect in later years. The initial yield penalty was attributed to reduced N availability, but much of this N could be remineralised in later years to support the decomposition of straw.

In Norway, Børresen (1999) found that leaving straw residues on the soil surface increased cereal yields by an average of 0.29 t/ha, relative to burning, removal or incorporation, with the yield benefit being larger when double the usual amount of straw was spread (due to reduced evaporation from the soil). However, surface straw residues reduced yield relative to the other management methods in one unusually wet year. In 6 long-term experiments Turley *et al*. (2003) found straw incorporation by tines reduced cereal yield by an average of 8% relative to straw burning followed by tine cultivation, which was attributed mainly to weed effects. Poorer, less consolidated seedbeds following straw incorporation may also have contributed.

Table 8. Summary of studies on the effects of straw management on crop yield.

Site(s)	Year(s)	Crop(s)	Treatments	Yield results	Reference
Heavy gleic fluvisol, Czech Republic	1974-2000	Spring barley (continuous)	Incorporation, removal or burning	Burning>incorporation>removal	Procházková *et al*., 2002
UK		Winter oats after wheat	Chopping or removal, followed by incorporation by ploughing, shallow cultivation or direct drilling	No significant differences	Christian & Miller, 1986
Clay soil, UK	1982-1988	Winter wheat	Chopping, burning or removal, followed by direct drilling or incorporation to 5, 15 or 25 cm	With direct drilling, straw chopping reduced yield by 1/3 relative to burning. Incorporation to 5 cm reduced yield by 1/5.	Christian *et al*., 1999
Loam and silty clay loam, Canada	1983-2009	Barley monoculture to 1996 then wheat/barley, OSR, triticale, pea rotation	Incorporation or removal	Incorporation >removal, in most site seasons	Malhi *et al*., 2011
Six clay , clay loam or silty clay loam sites, UK	1984-1994	Mostly winter wheat, some OSR, peas, barley, beet, linseed and triticale	Chopping or burning followed by tine	Burning> incorporation	Turley *et al*., 2003
Light soils, UK	1984-1997	Arable rotations	Incorporation or burning	No consistent yield effects	Silgram & Chambers, 2002
Flinty silty clay loam and sandy loam, UK	1985-1991	Winter wheat (continuous)	Chopping or burning, followed by various tillage treatments	No consistent yield effects	Prew *et al*., 1995
Clay loam, Scotland	4 seasons	Winter barley	Chopping or removal, followed by ploughing or shallow incorporation	Incorporation>removal	Ball & Robertson, 1990
Loam and silty clay loam, SE Norway	1991-1996	Spring barley, spring oats, spring wheat	Chopping, burning, removal, shallow incorporation, or deep incorporation	Surface residues increased yield except in one very wet year.	Børresen, 1999
Loam, Canada	1998-2001	Barley, pea, wheat, oilseed rape	Retention or removal, followed by zero or conventional tillage	Straw retention increased yield in one season (oilseed rape)	Malhi *et al*., 2006
Sandy loam and clay loam, Canada	2000-2004	Barley, oilseed rape	Retention or burning, followed by zero or conventional tillage	No consistent yield effects	Kutcher & Malhi, 2010
Semiarid, subtropical highlands, Mexico	2004, 2006, 2008	Wheat, maize	Residues removed or left, followed by zero tillage or incorporation	Yields higher when residues kept, for both maize and wheat and both tillage regimes	Verhulst *et al*., 2011
Clay Loam, Carlow, Ireland	2009-2011	Winter Wheat	Chopping or removal, followed by ploughing or reduced tillage.	No significant differences	Brennan *et al,* 2014
Light and heavy soil types. Carlow, Ireland	2001-2001	Winter Barley and Winter Wheat	Chopping or removal followed by ploughing or minimum tillage.	No significant differences.	Kennedy *et al,* 2013

4.6. Summary and conclusions

Weeds

- For most grass weed species, the persistence of seeds on the soil surface was unaffected by covering with chopped straw, but for black-grass *(Alopecurus myosuroides)* straw cover significantly increased persistence.
- Small reductions in residual herbicide activity have been observed where straw is chopped and spread. Generally cultivation regimes are not altered to account for this and it is not a significant factor in deciding whether to chop or bale.
- The agronomic and economic consequences of straw management on weed control are slight and not of major significance when deciding how to manage straw.

Pests

- There is little national survey data on crop yield losses due to pests.
- Without molluscicide treatment wheat and OSR crops would lose an estimated 5% and 4% of their yield, respectively, with some recent research suggesting that wheat may be as vulnerable to yield loss from slugs as OSR.
- Slug numbers have been shown to approximately double each year that straw is incorporated rather than removed.
- In most situations with low slug populations and low disease pressure, the difference between straw removal or incorporation is not likely to be important.
- When slug populations are high, the decision whether to chop or bale straw may have a significant agronomic impact through slug damage and costs of control, with the estimated benefit of straw removal around £20/ha.
- Straw management may affect BYDV levels by influencing aphid predator numbers, as well as direct effects on the disease-carrying aphids.
- For other pests the decision whether to bale or chop straw is not agronomically important.

Diseases

Cereal straw removal will not usually aid disease control as most inoculum is produced on stubbles. Whilst straw incorporation can reduce incidence of eyespot and other diseases, this is unlikely to make an economically relevant impact on the decision whether to remove or incorporate the straw.

- Most initial septoria infections are via long-distance dispersal of air-borne ascospores, so local straw residue management is unlikely to have a noticeable effect.
- Straw incorporation has inconsistent effects on foliar diseases because the amount of primary inoculum is a minor factor in eventual disease severity. The effects of straw management on overall crop growth and crop microclimate may be more important factors.

- The benefit from straw removal was estimated at *c.*£30/ha for bad infections of light leaf spot, *c.*£50/ha for verticillium and *c.*£100/ha for sclerotinia, although further work is required to verify these estimates.

Crop establishment

- The impact of straw incorporation on crop establishment on farms with modern cultivation equipment was not considered to be important in decision making.

Yield

- The effects of straw management on crop yield were inconsistent probably because the yield also depends on other factors including soil and weather conditions, nutrient management, and weed, pest and disease pressures.

5. Mechanical, logistical and fuel use impacts

Growers make decisions on whether to either chop and incorporate, or bale and remove straw based on a number of factors that are specific to individual fields, rotational positions and farm type (arable vs. mixed), as well as on the weather conditions. For arable farmers, the main considerations will often be:

- ease of harvesting,
- timeliness of the following cultivations
- effect on establishment of the succeeding crop.

Many growers have enough equipment and man-power to cultivate fields immediately after combining. The additional requirement to bale and remove straw inevitably delays the opportunity for immediate cultivation, and if wet weather intervenes, this delay can be considerable.

Towards the end of harvest the risks and consequences of delays to cultivation due to unbaled straw or uncollected bales becomes greater as the risks of delays to sowing increases, especially for OSR establishment. Anecdotally, some practitioners claim benefits of straw incorporation to soil friability, for example with some direct drilling systems. On the other hand, straw removal can increase the operational effectiveness of some cultivation and establishment techniques in moist conditions, especially for some minimum tillage systems which can be blocked by large quantities of chopped straw bridging between tines or balling up underneath the implement. For example, removing straw can be of benefit in the operation of sub-cast sowing of OSR.

The practical considerations of straw fate have not been discussed in detail for current farming and cultivation systems, nor their importance quantified. The main considerations are set out below, although some further structured survey work could be useful to help quantify these considerations and aid in answering some policy questions.

5.1. Dealing with straw – choices and current situation

Developments in straw choppers, balers and bale handling systems since the 1980s have increased efficiency, reduced labour and increased the speed of dealing with straw, whether it is baled and removed, or chopped and incorporated. Whilst straw choppers have remained fairly similar in their design and performance, there remains a considerable range in the package shape, size and density of bales, and the mechanical handling systems used to clear straw from the field. These are briefly described below.

5.1.1. Straw chopping

During combining, straw and chaff pass to the rear of the combine where it is either laid down as a swath for collection, or the straw is passed over a bank of rotating knives that chop it into short lengths. This is then spread across the full working width of the combine by vanes or horizontally rotating paddles. The chaff is also usually spread to a wide width. Whilst designs vary slightly, the job is essentially completed in the same manner by all combine manufacturers. All modern combines in the UK market are equipped with straw choppers and the number of machines currently operating without them is very low, and as these tend to be older and of small capacity, the proportion of crop area cut by them is insignificant. With modern electronic control, choppers can be switched on or off from the operators platform very easily, leading to increased flexibility and selective chopping within a field. Often a farmer may chop headlands so that lain swaths are not driven over, but leave the rest of the field for baling. This adds to the uncertainty of total baled areas in the UK. Chopping in the swath as a separate operation is rare now, but may be used in very wet years to dispose of swaths that have begun to rot. Compared to straw chopping in the 1980s straw is now cut to shorter lengths and spread more effectively than was common when work was undertaken for the straw burning ban.

5.1.2. Baling straw

Straw bales come in various shapes and sizes from small rectangular bales, through round bales to large square bales (Table 9).

Table 9. Straw bale dimensions and properties

Bale	Bale size (m)			Density	Weight
	width	Height	length	(kg/m^3)	(kg)
Small rectangular	0.4	0.5	0.9	117	20
Small round	1.2	1.5		118	250
Large round	1.5	1.8		103	400
Small square	0.8	0.9	2.5	160	280
Medium square	1.2	0.9	2.5	160	420
Large square	1.2	1.3	2.75	140	550

Small Bales

The small rectangular baler developed early in the 1940s produced bales of a suitable size and shape to be handled manually before mechanised handling systems were developed. Although the work rate is low (6 t/hr), there is still a demand for the small bale on some smaller farms.

Round Bales

The round baler has been on farm since the 1970s. It allows a faster baling speed, with typical rates of around 10 t/hr (25 to 35 bales/hr). The density of a round bale is similar to that of conventional bales, but well below that of big squares. Due to this, and the inefficient storage of a round package, there has been a significant move towards big square bales since the late 1980s. The shape also limits the size of the transport load, so round bales are mostly used on-farm, transported only short distances and stored outside. Despite this, the round baler remains popular with livestock farmers, especially as they are used for silage as well as for straw harvesting, and the bales are well suited to feeding and bedding systems. On a weight for weight basis handling systems equal the best of the small bale systems.

Square Bales

Large square balers have become the most efficient method of removing straw from the field, with high work rates of 20 to 25 t/hr (45 to 50 bales/hr), double the output of a round baler and quadruple that of a small rectangular baler and achieving bale densities up to 30% higher with each bale weighing up to 550 kg (Table 9). Self-loading trailers (bale chasers) can clear fields quickly, making them popular with large contractors who can justify the significant investment. The high output of these balers and associated systems is also attractive to the large arable farm as fields can be cleared rapidly, to allow cultivation for the following crop.

Large square bales can be less popular with livestock farmers, as handling is difficult on farms where machinery has a limited handling capacity. For this reason a range of small to medium sized square balers were developed in the 1990s giving more manageable sized bales but still achieving reasonable work rates and the same density to be attractive to contractors and merchants.

5.1.3. Who bales on the farm?

On most arable farms where straw is not used on farm or actively sold on the market by the farmer, baling and straw removal would normally be undertaken by the straw purchaser or a contractor. There are a number of situations which may influence on the farmer's attitude towards straw removal:

- Baling for on farm use by the farmer; removal and storage by the farmer
- Baling for on farm use by a contractor; removal and storage by the farmer
- Baling for sale by the farmer; removal and storage by the farmer
- Baling for sale by a contractor; removal and storage by the farmer
- Sale/swap to a neighbour; baling, removal and storage by the neighbour
- Sale/swap to a neighbour; baling by a contractor; removal and storage by the neighbour
- Sale to a merchant; baling, removal and storage by the merchant

The decision to remove straw depends on who is doing the baling and removal, the machinery they are using, the care they take regarding soil compaction (e.g. driving on tramlines rather than across fields) and their availability and timeliness. Overall however the decision will largely be based on:

- whether the straw price is perceived to exceed the value of nutrients and SOM removed,
- the requirement to establish the following crop
- attitudes towards soil compaction and health.

This review explores these considerations in more detail.

5.2. Ease and speed of harvesting

Leaving straw in the swath rather than chopping can free up combine engine capacity, as a straw chopper could consume up to 20-25% of installed engine power. This equates to a potential extra *c.*10 ha harvested each day on a large modern combine, but in reality, factors other than engine power generally limit forward speed, such as the header intake of crop, the efficiency of the grain separation of the combine related to conditions, and the grain handling capacity of the infrastructure behind the combine. Chopping straw is a more onerous and power consuming task when the straw is not properly fit (early in the season) or is damp (e.g. after dusk). It is at these times when the chopper may noticeably slow combining speed and increase fuel consumption. In some situations this may sway the decision to disengage the chopper and leave the straw, for example if the crop is fit enough to thresh but chopping is slowing progress.

Some combine operators empty on the move, with tractor and trailer running alongside to minimise interruption to harvest. The underbelly clearance of modern machinery is sufficient to straddle swathes so these do not generally impinge harvest operations (obstructions such as drawbar stands on grain trailers can catch straw and cause it to ride up between the tractor and trailer, although drawbar stands are usually easily detachable). However, where swathes have been rolled by the grain transport trailer this can impact on subsequent baler operation, and could influence the decision to prefer straw chopping. Leaving straw in swathes can be more problematic on fields where combining is difficult (e.g. with lodging); if the combine frequently has to stop and reverse to clear the cutting header from blockages then large heaps of straw are formed in the row which can be difficult to bale. Whilst these considerations are usually not the primary factors in deciding whether to chop or bale fields, they often play a part in the decision process, and selective chopping may be practiced (e.g. on headlands when straw on the rest of the field is left).

5.3. Fuel and machinery costs

5.3.1. Baling costs

Chopper power usage is very variable depending on crop conditions. Discussion with one of the machinery manufacturers (Claas) suggests that a modern combine chopper takes an average of about 50 to 75 kW (70 to 100 hp) which could use up to 15 litres of fuel per hour.

Laying swaths can use up to 30% less fuel by the combine in wet straw. An average combine consumes 15 to 20 l/ha of diesel fuel, meaning that running the chopper can use up to 6 l/ha. At a current diesel price of £0.70/litre, this equates to up to £4.20/ha saving in fuel costs for laying swaths. To replace a bank of combine chopper blades costs around £1,000. Assuming a set of blades will chop straw from 1,000 ha the cost of wear on blades is around £1/ha. This could total up to £5.20/ha costs for chopping straw in worst conditions (£1.59/t based on average 3.4t/ha straw yield). The National Association of Agricultural Contractors (NAAC) suggests a charge of £6.79/ha on top of £85.24/ha combining rate for cereals, meaning that chopping accounts for about 7% of combining costs (contractor cost of £2.00/t on average 3.4 t/ha straw yield). This charge includes chopper maintenance, fuel, blade wear and associated labour.

The NAAC give baling costs as per bale contract charges, which have been converted into £/t for comparison (Table 10).

Table 10. Baling costs, by contractors (data from The National Association of Agricultural Contractors 2013/14) and by farmers (Nix, 2013).

Bale	Bale size (m)			Contracting charge	Bale weight	Contracting charge	Farmers average cost
	width	height	length	(£/bale)	(kg)	(£/ton)	(£/bale)
Small rectangular	0.4	0.5	0.9	0.55	20	27.50	0.29
Small round	1.2	1.5		2.75	250	11.00	2.23
Large round	1.5	1.8		3.25	400	8.12	2.23
Small square	0.8	0.7	2	3.60	120	29.99	
Medium square	1.2	0.7	2.5	4.45	420	10. 60	4.04
Large square	1.2	1.3	2.75	6.75	550	11.36	5.70

N.B. Charges quoted exclude stacking and bale handling costs. These would be extra (see below).

5.3.2. Carting costs

Field clearance and storage costs vary depending on the method of bale clearance and who undertakes the task. The following examples are given for a field to stack distance of 2 km with all work carried out by a contractor. Costs to farmers undertaking this work themselves may be approximately 20% less, excluding machinery depreciation costs.

Two tractors and trailers with a telescopic handler loading/unloading bales at each end would cost £147/hr for contract hire and could be expected to shift in the region of 30t/hr. This would give a handling cost of £4.90/t. A single self-loading chaser system could be expected to shift 20t/hr in the same scenario but cost £40/hr, giving a handling cost of £2.00/t. Stacking small bales in heaps of 56 with a telescopic handler and then carting them with a tractor and stack-shifter would cost around £73.50/hr and move 3 t/hr to the yard, making it more expensive at £24.50/t. A number of scenarios demonstrating costs are shown in Table 11.

On the road, articulated 44t lorries are charged at around £0.97/km. Due to the low bulk density of straw, the maximum weight of straw is around 20t per load. This gives a transport cost of around £0.049/t/km. This figure is very variable and even straw haulage companies struggle to give an estimate. Searcy *et al*. (2007) considered the cost to be higher than this, more like £0.08/t/km. Based on this first estimate, a lorry of straw leaving East Anglia would be bought for around £1120 (£56/t) and by the time it reached Wales, would be sold for around £1352 (£67.60/t).

In summary, a farmer who sells straw in the swath at £8-£15/t (*c*.£25-£50/ha) rather than chopping it for incorporation may expect to also save £4-£5.20/ha by not chopping. A farmer who bales, carts and stores his straw will typically spend around £10/t (£35/ha) baling and £5/t (£17/ha) clearing an average 3.4 t/ha of straw, giving total costs of £15/t (£52/ha). At a typical straw market price of £40-£60/t the straw would be worth between £135 and £205/ha, giving a net return of around £80-£150/ha.

Table 11. Total costs of straw, including baling and carting, in various scenarios.

Scenario	Methods	Cost of straw (£/t)*	Baling cost (£/t)	Carting cost (£/t to yard, 2 km away)**	Total cost (£/t)
Livestock farmer buys straw in swath but has own equipment	Round bales, carted using teleporter and trailers	11.00	5.73	4.90	21.63
Livestock farmer buys straw in swath but has own equipment	Small bales, carted using flat eights in 56 heaps	11.00	14.50	24.50	50.00
Livestock farmer, buys straw in swath, contractor bales and collects	Big bales, carted using chasers	11.00	10.83	2.00	23.83
Contractor, buys straw in swath and runs own equipment	Big bales, carted using chasers	11.00	9.55	2.00	22.55
Arable farmer, owns straw and has own equipment	Big bales, carted using telescopic handler and trailers	Saving of 1.59 ***	9.55	4.90	12.86

* Price paid for straw in swath £8-15/t (£25-50/ha). Median figure of £11/t.
** Full contracting costs given, farmer cost likely to be 20% lower
*** Based on savings from not having to chop straw (£5.20/ha farmer cost, average 3.4 tons of straw/ha).

5.4. Subsequent crop establishment

Incorporating straw is not normally a problem where the appropriate tillage equipment is at the farmer’s disposal, and has not been the problem as anticipated when the straw burning ban was introduced over 20 years ago. This is because:

- modern cultivation equipment is designed to deal with chopped straw on the surface;
- modern combines are more effective at chopping and spreading straw & chaff;
- modern varieties are shorter than varieties 20 years ago.

Problems may be encountered in some conditions, if residues are spread unevenly at headlands and form piles of chaff in the field that become coagulated and sticky when damp. In damp conditions where large amounts of wet, chopped straw is present it can ride up on cultivator tines or on drill coulters causing blockages. In very dry conditions with hard soils, chopped straw can give problems with traction, as the tractor tyres or tracks can lose traction efficiency on the straw. In such situations a prior pass with discs, a press or a harrow can usually remedy the problem.

5.4.1. Ploughing

Chopped straw is generally buried easily with modern ploughs. Skimmers fitted above the mouldboards aid straw burial and help ensure that the straw is mixed through the soil rather than left in a layer at the bottom of the furrow. Where residues are uneven, piles of straw or chaff may sometimes cause blockages between the mouldboard and the skimmer blade, though this is rarely a significant problem. Subsequent cultivations following ploughing are generally unaffected if straw is buried effectively by the plough.

5.4.2. Non inversion tillage, or ‘minimum’ tillage

There are a wide range of ‘minimum tillage’ cultivation and establishment systems in use, all of which have been designed with residue management in mind, given that chopped straw is so common. Views differ on how best to deal with residues; many believe that they are best left on the surface and that soil disturbance should be minimal, whereas others incorporate by mixing with as much as 150 to 200mm soil.

Straw harrows are increasingly used as a first pass after combining, levelling straw and harrowing at a very shallow depth to aid residue decomposition and encourage weeds and volunteers to germinate in a stale seedbed to be cultivated some weeks later. Other cultivators were designed specifically to incorporate residues (including standing cover crops) with discs, tines or knives.

The majority of current one-pass cultivators can cope with a cereal or OSR field that has been cut and chopped by a modern combine. High frame ground clearance and staggered rows of discs and/or tines that work well at high speeds of 8-15 km/hr are among the recent developments allowing modern cultivators to cope well in high residue conditions without blockage problems. There is little to choose between disc or tine cultivators. Discs chop debris in addition to mixing, and tines rely more on a throw action for mixing the soil. Ideally cultivators should be fitted with both, but the discussion is still open on which way round is best. Cultivators that have rakes or harrows following the rear roller are likely to become blocked with straw if it is damp. Light-weight tine or disc cultivators struggle to incorporate large amounts of straw as the implement will ride over the straw surface rather than digging in. Where one pass is not sufficient to bury residues, another pass may have to be made, ideally at an angle to the preceding.

5.4.3. Sub-cast drilling

OSR is now commonly sown directly behind a cultivator, often with some form of sub-soil tine. Tall, standing stubble is valued by some as it is thought to discourage pigeons. In wet conditions, straw can become tangled under cultivators due to their low underbody clearance. For this reason, and because chopped straw can encourage slugs (for details see section 4.2.1), some growers prefer to remove straw before the establishment of OSR by sub-casting.

5.5. Weather and timeliness of baling and straw removal

Where a large farm has separate harvesting and cultivation teams, it is common practice for a cultivator to begin in a field before the combine has left it. Obviously, with baling and bale removal being a relatively long operation, this approach leaves no time in the schedule for baling to occur, particularly where OSR is the following crop and needs to be sown by mid to late August. Unpredictable weather (or a poor forecast) exacerbates this problem, and as the harvesting season progresses, cultivations become more urgent. Thus a farmer may be willing to sell straw in the swath at the beginning of the season when fine weather is attendant but unwilling late in the season if long periods of rain are forecast. The proportion of straw chopped or baled is therefore changeable as the season progresses, and difficult to predict at the start.

A large farm with a dedicated cultivation team will have the equipment and the staff to cover the acreage required, but often with limited spare capacity. Any time lost waiting for straw to be cleared may cause delays that have impacts through the season, ultimately delaying sowing. The earlier the first cultivation occurs, the more time there is for weed germination and soil weathering before final cultivation and establishment. Whilst in practice the impact of a one or two day delay may be agronomically insignificant, a delay of a week or more might necessitate an extra herbicide application or an extra cultivation pass. Similarly, the impact of a delay in establishing OSR, especially into early September, may be substantial, particularly if followed by a cool autumn and winter. In a season such as 2012/13 this delay could have made the difference between having an adequate crop to withstand slug and pigeon pressures, and crop failure.

The timescale of straw removal is therefore important, as is the trust a farmer has in local merchants and contractors to carry out an efficient job. Many straw contractors that cover thousands of hectares may continue buying straw in the swath even when they have a couple of day's backlog (either due to bad weather or machinery constraints). This could occasionally mean that a farmer will have straw on his field long after he wanted to cultivate and be discouraged from selling straw in the future. But a farmer who is baling for his own use, to market himself, or has a good rapport and level of trust with a contractor, is much more likely to lay the straw in swaths and take the risk of delayed cultivations.

5.6. Summary and conclusions

- A farmer who sells straw in the swath at £8-£15/t (*c*.£25-£50/ha) rather than chopping it for incorporation may also expect to save £4-£5/ha from not chopping straw. A farmer who bales, carts and stores his straw will typically achieve a net return of £80-£150/ha.

- Straw fate can be swayed by the practicalities of cultivation and establishment. This depends on the individual farm situation, the quantity of straw, and the quality of chopping, soil conditions, and the cultivation equipment to be used.
- Towards the end of harvest the consequences of delays to cultivation due to unbaled straw or uncollected bales become greater as the risk of delays to sowing increases, especially for OSR establishment. However, in a normal year, the worst result of delayed straw removal is to delay cultivations by a few days.
- In a worst case scenario, swaths lying in a field could totally prevent autumn cultivations and sowing. Spring drilling would incur the cost of new seed and reduced yields, with gross margins likely to be reduced by £100/ha or more. This can also impact on the subsequent rotation as the harvest of a spring sown crop is likely to be late, again potentially having large financial implications.
- Straw removal can increase the operational effectiveness of some cultivation and establishment techniques in moist conditions. Others contend that straw at the surface can improve effectiveness of some cultivation and direct drilling systems.
- The decision to remove straw is often subjective, based on tradition and the relationship the farmer has with purchaser of the straw and those who will remove it.

6. Cost benefit evaluation and decision support

6.1. Costs and benefits of straw incorporation vs removal

6.1.1. Economic and practical considerations

Determining precise estimates for the economic cost or benefit of straw incorporation or removal is very challenging due to the wide range of situations on farm that affect the costs of dealing with straw (whether chopping or baling) and its impact on the soil, weeds, pest and diseases, subsequent cultivation and establishment, and ultimate effects on following crop yields. However, there are aspects for which more definite values can be ascribed. By assessing the information on the economic costs or benefits, as well as the other factors affecting the decision making process, farmers can make better judgements of the value of their straw. The key considerations are listed below and the economic consideration summarised for wheat and OSR straw in Tables 12 and 13, respectively:

- Not chopping straw will save around £4-5/ha in fuel and machinery wear costs. There may or may not be an associated increase in combine output, depending on the constraints to harvest speed on the farm.

- The nutrient value of straw can be calculated from straw yield (t/ha fresh weight) multiplied by nutrient content (1.2, 9.5 and 1.3 kg/t for P_2O_5, K_2O and MgO in wheat straw; 2.2 and 13.0 kg/t for P_2O_5 and K_2O in OSR straw, respectively) multiplied by their financial value (currently £0.73/kg P_2O_5, £0.54/kg K_2O and £3.40/kg MgO). At typical yields, the current nutrient value for wheat straw is £3/ha for P_2O_5, £17/ha for K_2O and £15/ha for MgO; for OSR values are £3/ha for P_2O_5 and £13/ha for K_2O.

- The nutrient value of straw should only be considered at soil P and K Indices of 2 and below, and for Mg at Index 0 for cereals, Index 1 for OSR or Index 2 if a responsive crop such as potatoes is in the rotation.
- The impact on SOM levels of a single year of straw incorporation is low and an economic value cannot be ascribed; other bulky organic materials (e.g. FYM, compost) are more effective at building SOM levels. However, in the absence of other organic material additions on soils with low SOM levels (<5% organic matter), periodic incorporation of straw is advised to maintain SOM levels.
- If straw removal risks a delay to cultivations, a judgement should be made of the likely impact; this will be dependent on the farm set-up and individual circumstances.
- The risk and impact of straw removal causing soil compaction should be considered; this will depend primarily on soil type and forecast weather. The costs of soil compaction and its remediation can be high (*c*.£55/ha).
- Straw incorporation can have a beneficial effect on the control of cereal diseases such as eyespot and fusarium, though the impact is unlikely to be agronomically (or economically) significant.
- Incorporating diseased OSR straw is likely to worsen infection of nearby and subsequent OSR crops for sclerotinia, light leaf spot and verticillium wilt. Whilst experimental data are not available, expert opinion suggests that for heavily infected crops, yield loss from these diseases might be reduced by up to 50% by removing straw. The economic impacts in high risk situations could range from *c.*£30-£100/ha.
- Incorporating straw is likely to increase slug populations. Although evidence is limited, the presence of straw could double damage to the succeeding crop, which in vulnerable situations could be costly (*c*.£20/ha). Impacts are perceived to be worse for OSR establishment and where OSR straw is incorporated.

Once the economic value of straw incorporation is assessed (i.e. the nutrient value, net of saved chopping costs) this can be compared to the market value of straw for sale in the swath (see Appendix 1). The difference between these values can be taken as an indication of the other costs/benefits and the perceived inconvenience to the farmer of either incorporating or removing straw. Assuming a wheat straw value of £15/ha (3 + 17 – 5, for P, K and saved fuel respectively), accepting a straw sale price of £18/ha implies (from the small margin) that the farmer sees some benefit in removing straw (or is not fully aware of the straw's nutrient value). In contrast, a farmer who rejects an offer of £50/ha must either see more value in the incorporated straw or feel that avoiding the inconvenience and risks of straw removal on compaction and delayed cultivations and establishment is worth more to him than £35/ha.

6.1.2. Environmental considerations

Fuel use and associated GHG emissions are lower per hectare for incorporated straw than baled and removed straw. Williams *et al*. (2006) calculated energy use for a combine harvester to be 1096 MJ/ha without chopping straw and 1134 MJ/ha with straw chopped, giving straw chopping an energy cost of 38 MJ/ha. Fuel use accounts for 68% of these costs, and manufacture for the 32% remainder. GHG costs can be calculated using an emission factor 0.0864 kg CO_2e/MJ for fuel and 0.11 kg CO_2e/MJ for manufacture giving total GHG costs of 103, 107 and 4 kg CO_2e/MJ respectively for combining without chopping, combining with chopping, and for chopping itself. By contrast, the energy costs for baling are 298 MJ/ha, 77% of which is fuel energy, giving a GHG cost of 28 kg CO_2e/ha. These values are small in relation to the total GHG emissions from a wheat crop of around 4000 kg CO_2e/ha (Berry *et al*., 2010), much of which is related to N fertiliser use.

Table 12. The economic costs and benefits of removing wheat straw.

Cost / benefit	£/ha	Comments
Fuel savings	4-5	Fuel saved by not chopping straw
Nutrient losses		
N	0	Doesn't affect fertiliser N requirements
P	-3	If soil index 2 or lower
K	-17	If soil index 2 or lower
Mg	-15	If soil index 1 or lower
S and other nutrients	0	Not sufficient to affect fertiliser use
Soil organic matter	0	Single year impacts considered to be negligible*
Agronomic impacts		
Reduced slug populations	0 to 24**	Assumes slug damage decreases yield by 2% if straw not removed, or additional slug pellet applications required.
Increased eyespot incidence	0	Dependent on eyespot severity, control and its yield impact, but likely to be inconsequential.
Weeds	0	Negligible impact on effectiveness of residual herbicides
Soil compaction	0 to -55	Dependent on soil conditions

Negative values denote costs; positive values denote savings.
*There may be long-term impacts on SOM if straw additions are not replaced by other organic amendments.
**Assuming wheat yield of 8 t/ha and value of £150/t.

Table 13. The economic costs and benefits of removing oilseed rape straw.

Cost/benefit	£/ha	Comments
Fuel savings	4-5	Fuel saved by not chopping straw
Loss of nutrients		
N	0	Doesn't affect fertiliser N requirements
P	-3	If soil index 2 or lower
K	-13	If soil index 2 or lower
Mg	0	Only if soil index 1 or lower
S and other nutrients	0	Not sufficient to affect fertiliser use
Soil organic matter	0	Single year impacts considered to be negligible*
Agronomic impacts		
Reduced slug populations	0 to 20**	Assumes slug damage decreases yield by 2% if straw not removed, or additional slug pellets applications required
Reduced light leaf spot	0 to 30**	Average 10% yield loss (up to 50%) reduced 30% by straw removal
Reduced verticillium wilt	0 to 50**	5% fields heavily infested. These suffer average 10% yield loss, reduced 50% by straw removal
Reduced sclerotinia	0 to 100**	Average 20% yield loss, reduced 50% by straw removal
Weeds	0	Negligible impact on effectiveness of residual herbicides
Soil compaction	0 to -55	Dependent on soil conditions

Negative values denote costs; positive values denote savings.
*There may be long-term impacts on SOM if straw additions are not replaced by other organic amendments.
**Assuming oilseed rape yield of 3.5 t/ha and value of £300/t.

As well as a slight reduction in fuel use compared with removal, incorporating straw could give GHG benefits through increased C sequestration. The potential CO_2-C savings that could be achieved if all cereal straw was incorporated Great Britain amount are estimated to be 1730 kt CO_2-e (see Section 3.5). However, this may not be a genuine additional saving (against a present day baseline), as a large proportion is already incorporated (either as straw or with FYM). Indeed, using cereal straw as a fuel source is likely to lead to greater CO_2-e savings than any potential additional soil C storage from straw incorporation. The effect of crop residue incorporation on N_2O (a GHG with a global warming potential *c.*300 times greater than CO_2) emissions is a subject of on-going research. In terms of water quality impacts, there is some evidence that straw incorporation can reduce over-winter nitrate leaching losses and P losses to surface waters.

If straw removal reduced slug populations this may reduce molluscide applications with particular benefits if metaldehyde use was reduced, as this has been found in water supplies and is subject to current concern.

Overall, the environmental benefits or otherwise of incorporating straw are dependent on its alternative use, especially whether it can displace energy generation feedstocks derived from fossil fuels.

6.2. Decision support

The decision whether to chop or bale (or at what price to sell) straw is farm specific and consideration should be made of the key factors outlined above. A decision support tree (Figure 2) has been developed to consolidate this information and to help growers decide whether to soil incorporate or sell their straw. It should be used with the accompanying notes.

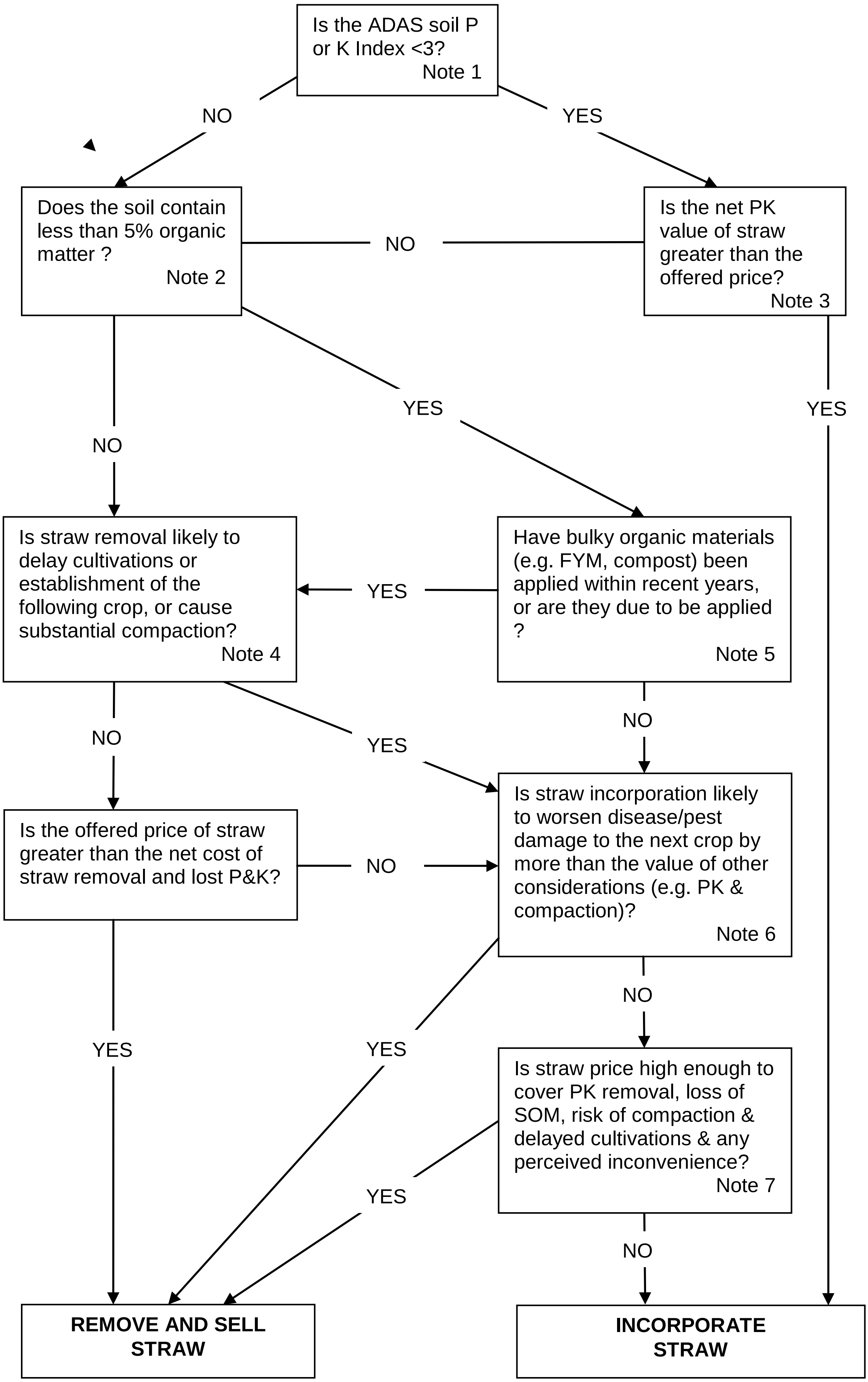

Figure 2. Decision support tree to help farmers decide whether to soil incorporate or remove straw.

Notes to Figure

1. Crops grown on soil at P and K Index 0 and 1 would be expected to respond to the extra amounts of phosphate and potash supplied by incorporating straw. For soils at Index 2, straw additions will contribute towards the amount of phosphate and potash required to replace that taken off with the previous crop (See "Fertiliser Manual (RB209)").
2. Soils low in organic matter (i.e. less than 5% organic matter) are thought to benefit most from the organic matter supplied by straw (and other bulky organic materials) in terms of improved soil structure and moisture holding capacity.
3. Calculate the monetary value (£/t) of the nutrients in the straw using the guidance in Table 2. If the straw nutrient value exceeds the cost of purchasing the equivalent quantity of 'bag' P and K, it may be more beneficial to incorporate the straw rather than to remove it for sale.
4. It may be important to cultivate quickly after sowing, for example to establish the next crop or to create a stable seedbed. The risks and consequences of delays will depend on whether it is early or late in the season, the weather, how the straw is being cleared, and the capacity to 'catch up' with cultivations. The risks and consequences of compaction from straw removal will be worst in wet years on heavy soils, but will also depend on how the straw is cleared.
5. Applications of bulky organic materials such as solid livestock manures, compost and biosolids can build up SOM levels more effectively than straw. If bulky organic materials are applied to the field during the rotation, straw incorporation is not necessarily required for maintaining SOM levels.
6. Straw incorporation can increase the risk of pest and disease damage, especially from slugs, but also from sclerotina, phoma and verticilium wilt in OSR. Cereal diseases are unlikely to be exacerbated by straw incorporation, as the evidence shows eyespot risk to *decrease* with incorporation. Only in conditions of high slug or disease pressure is the likely damage from incorporation expected to outweigh other considerations.
7. The sale price of straw will depend on the local market, whether straw is sold in the swathe or baled, and how it is baled. In making the final decision whether to chop or bale the following factors should be taken into account, including the cost of chopping (~£5/ha), the PK value of the straw, the perceived SOM value of incorporation, the risks of delay and compaction from removal, and the risks of increased pest (slug) or disease damage from incorporation.

7. Conclusions

The fate of straw is subject to increasing debate as new markets come on stream and as farmers and agronomists increasingly recognise the importance of maintaining SOM. Anecdotal evidence has suggested that straw incorporation improves in soil quality, workability and ultimately yields. However, long-term field experimental studies have shown that the increases in SOM from straw incorporation are small and only apparent after several years. Soil physical condition has also been shown to improve following straw incorporation, but only after at least eight years of repeated additions. Whether this is because the field experiments conducted to date have not compared the appropriate systems and do not have sufficient precision to recognise agronomically important yield effects (i.e. experiments rarely detect significant differences of <0.3 t/ha, yet this effect would be worth over £50/ha at current prices), or because the effects genuinely are negligible remains to be seen. In this context, it is noteworthy that soils, and in particular SOM levels and inherent physical properties, are resistant to change in the short-medium term (i.e. <10 years).

It is, however, clear that farmers should seek to maintain or improve SOM levels. If SOM needs to be increased, a more effective way is through additions of bulky organic materials such as solid livestock manures, compost or biosolids; if these additions are made on a regular basis then straw incorporation provides little additional benefit. The biggest difficulties come where SOM levels are low and bulky organic materials are not readily available. There is some geographic disparity in where most livestock manures are produced (i.e. western Britain) and where they are needed most (i.e. low SOM arable fields in the east of Britain). For farms with low SOM and without alternative sources of organic matter, straw incorporation may be the most effective method of maintaining SOM levels (or increasing them if straw has in the past routinely been removed). However, putting an economic value on straw for building SOM levels is not currently possible.

From a policy perspective, there is around 2 million tonnes of potentially available straw that could be sold rather than incorporated if the price was right. What a farmer deems to be the ‘right’ price to switch from incorporation to removal will depend on a wide range of factors specific to individual farm circumstances. Withdrawing 2 million tonnes of straw from incorporation would probably have a small impact on reducing SOM levels over the long term, although in principle this may be mitigated by the increasing availability of other organic materials such as composts and biosolids.

This review and the accompanying decision support tree should aid farmers in ascribing a value to their straw and in deciding on its fate. It should also help in estimating the quantity of straw that may be available for new markets given sufficient incentive for farmers to sell rather than incorporate. Given that there are both advantages and disadvantages to straw incorporation from agronomic and logistical perspectives, the ultimate economic decision of whether to chop or bale will continue to vary widely between farms.

8. Recommendations for further research

1. In deciding whether removing straw is the right policy for UK soils, further consideration is needed regarding the quantity of straw that can be removed from soils without negatively impacting SOM. This should take into account the quantity and availability of other organic material additions, and address the issue that organic resources may not be accessible where they are most needed.

2. There are a number of agronomic questions on the value of straw removal that warrant further study by experimentation, specifically the impact of straw incorporation or removal on disease carryover of sclerotinia, light leaf spot, phoma and verticillium wilt in OSR, and its impact on slug populations and damage.

3. This review suggests that straw utilisation may be higher than assessed in other studies; this has policy implications for the amount of straw potentially available for new markets. Studies giving greater confidence to estimates of production, utilisation and future demand are required to facilitate investment decisions in new facilities that use straw as a feedstock, and to prepare the livestock and arable industries for future market conditions.

4. Structured farmer surveys would be useful to answer policy questions such as 'how much more straw could become available for other uses and at what price?'

5. The decision support tree developed in this study could be coded within a calculator or app which may improve its usefulness to growers and allow more refined values or advice to be given.

6. New experimental techniques and approaches should be considered to investigate the impact of straw incorporation on soil quality and fertility. Because impacts are soil and system dependent, there can be no substitute for doing comparisons across a number of situations.

9. References

Addiscott T M, Dexter A R. 1994. Tillage and crop residue management effects on losses of chemicals from soils. *Soil and Tillage Research* **30**:125-168.

Al-Maliki S, Scullion J. 2013. Interactions between earthworms and residues of differing quality affecting aggregate stability and microbial dynamics. *Applied Soil Ecology* **64**:56-62.

Bailey R. 1990. *Irrigated Crops and their Management*. Farming Press Ltd.

Bailey A, Deasy C, Quinton J, Silgram M, Jackson B, Stevens C. 2013. Determining the cost of in-field mitigation options to reduce sediment and phosphorus loss. *Land Use Policy* **30**:234-242.

Ball B C, Robertson E A G. 1990. Straw incorporation and tillage methods: Straw decomposition, denitrification and growth and yield of winter barley. *Journal of Agricultural Engineering Research* **46**:223-243.

BASF. 2013. *The pendimethalin of choice for weed control in minimal tillage systems*. http://www.agricentre.basf.co.uk/agroportal/uk/en/crops/autumn_cereal_solutions_1/products_1/stomp_aqua/minimal_tillage_systems/min_till_systems.html Accessed 3 July 2013.

Bateman G L, Coşkun H. 1995. Populations of *Fusarium* spp. in soil growing continuous winter wheat, and effects of long-term application of fertilizers and of straw incorporation. *Mycological Research* **99**:1391-1394.

Bateman G L, Murray G, Gutteridge R J, Coşkun H. 1998. Effects of method of straw disposal and depth of cultivation on populations of *Fusarium* spp. in soil and on brown foot rot in continuous winter wheat. *Annals of Applied Biology* **132**:35-47.

Berry P, Kindred D, Olesen J E, Jorgensen L N, Paveley N. 2010. Quantifying the effect of interactions between disease control, N supply and land use change on the greenhouse gas emissions associated with wheat production. *Plant Pathology* **59**:753-763.

Bhogal A, Chambers B J, Whitmore A P, Powlson D S. 2008. *Effects of reduced tillage and organic material additions on the carbon content of arable soils.* Report to Defra for project SP0561.

Bhogal A, Nicholson F A, Chambers B J. 2009. Organic carbon additions: effects on soil bio-physical and physico-chemical properties. *European Journal of Soil Science* **60**:276-286.

Bhogal A, Chambers B J, Whitmore A P, Young I. 2011. *Organic manure and crop organic carbon returns – effects on soil quality: SOIL-QC.* Final report for Defra Project SP0530.

Biederbeck V O, Campbell C A, Bowren K E, Schnitzer M, McIver R N. 1980. Effect of burning cereal straw on soil properties and grain yields in Saskatchewan. *Soil Science Society of America Journal* **44**:103-111.

Boguzas V, Kairyte A, Jodaugiene D. 2006. Weed and weed seed-bank response to tillage systems, straw and catch crops in continuous barley. *Journal of Plant Diseases and Proctection, Supplement* **20**:297-304.

Børresen T. 1999. The effect of straw management and reduced tillage on soil properties and crop yields of spring-sown cereals on two loam soils in Norway. *Soil and Tillage Research* 51:91-102.

Brennan J, Hackett R, McCabe T, Fortune R A, Forristal P D. 2014. The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. *European Journal of Agronomy* **54**:61-69.

Brown L, Armstrong Brown S, Jarvis S C, Syed B, Goulding K W T, Phillips V R, Sneath R W, Pain B. 2000. An inventory of nitrous oxide emissions from agriculture in the UK using the IPCC methodology:emission estimate, uncertainty and sensitivity analysis. *Atmospheric Environment* **35**:1439-1449.

Catt J A, Christian D G, Goss M J, Harris G L, Howse K R. 1992. Strategies to reduce nitrate leaching by crop rotation, minimal cultivation and straw incorporation in the Brimstone Farm Experiment, Oxfordshire. *Aspects of Applied Biology (Nitrate and Farming Systems)* **30**:255-262.

Christensen B T. 1986. Straw incorporation and soil organic matter in macro-aggregates and particle size separates. *European Journal of Soil Science* **37**:125-135.

Christian D G, Miller D P. 1986. Straw incorporation by different tillage systems and the effect on growth and yield of winter oats. *Soil and Tillage Research* **8**:239-252.

Christian D G, Bacon E T G. 1991. The effects of straw disposal and depth of cultivation on the growth, nutrient uptake and yield of winter wheat on a clay and a silt soil. *Soil Use and Management* **7**:217-222.

Christian D G, Bacon E T G, Brockie D, Glen D, Gutteridge R J, Jenkyn J F. 1999. Interactions of straw disposal methods and direct drilling or cultivations on winter wheat (*Triticum aestivum*) grown on a clay soil. *Journal of Agricultural Engineering Research* **73**:297-309.

Clarke J, Wynn S, Twining S, Berry P, Cook S, Ellis S, Gladders P. 2009. Pesticide availability for cereals and oilseeds following revision of Directive 91/414/EEC; effects of losses and new research priorities. *Research Review No. 70.* HGCA, Stoneleigh.

Colbach, N., Lucas, P., Cavelier, N., Cavelier, A. 1997a. Influence of cropping system on sharp eyespot in winter wheat. *Crop Protection* **16**:415-422.

Colbach N, Lucas P, Meynard J-M. 1997b. Influence of crop management on take-all development and disease cycles on winter wheat. *Phytopathology* **87**:26-32.

Colbach N, Saur L. 1998. Influence of crop management on eyespot development and infection cycles of winter wheat. *European Journal of Plant Pathology* **104**:37-48.

Copeland J, Turley D. 2008. National and regional supply/demand balance for agricultural straw in Great Britain. *CSL report to NNFCC.* http://www.northwoods.org.uk/northwoods/files/2012/12/StrawAvailabilityinGreatBritain.pdf

CRD. 2013. *Chemicals Regulation directorate databases*. www.pesticides.gov.uk/pestreg/default.asp Accessed 10/6/2013.

Dalal R C, Henderson P A, Glasby J M. 1991. Organic matter and microbial biomass in a vertisol after 20 yr of zero-tillage. *Soil Biology and Biochemistry* **23**:435-441.

Davies D B, Garwood T W, Rochford A D H. 1996. Factors affecting nitrate leaching from a calcareous loam in East Anglia. *Journal of Agricultural Science, Cambridge* **127**:75-86.

De Klein C, Novoa R S A, Ogle S, Smith K A, Rochette P, Wirth T C, McConkey B G, Mosier A, Rypdal K. 2007. N2O emissions from managed soils, and CO2 emissions from lime and urea application. *In: 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4: Agriculture, Forestry and Other Land Use. 54 pp.*

Defra. 2010. *Fertiliser Manual (RB209). 8th Edition*. TSO. PB13381.

Defra. 2011. *Agriculture in the UK*

Ellis S.A. & Berry P. 2013. Assessing tolerance to slugs in winter wheat and oilseed rape by simulating pest damage. *CRD Project PS2805*

Ellis S A, Berry P M 2011. PS2814 A desk study to review the potential for crop physiology based thresholds for invertebrate feeding groups. *CRD Project PS2814*

Fitton N, Ejerenwa C P, Bhogal A, Edgington P, Black H, Lilly A, Barraclough D, Worrall F, Hillier J, Smith P. 2011. Greenhouse gas mitigation potential of agricultural land in Great Britain. *Soil Use and Management*, **27**:491-501.

Fogelfors H. 1982. Collection of chaff, awns and straw when combining and its influence on the seed bank and the composition of the weed flora*. Proceedings of the 23rd Swedish Weed Conference - Weeds and Weed Control* **2**:339-345.

Frankinet M, Raimond Y. 1996. Essai permanent plots, Gembloux. *In: D.S. Powlson et al. (ed.) Evaluation of soil organic matter models. NATO ASI Ser. 1 Vol. 38:325-331.* Springer-Verlag, Berlin.

Gibbs, P A, Muir, I., Richardson, S., Hickman, G., & Chambers, B.J. 2005. *Landspreading on Agricultural Land: Nature and Impact of Paper Wastes Applied in England and Wales*. Environment Agency, June 2005.

Gladders P, Musa T M. 1980*.* Observations on the epidemiology of *Leptosphaeria maculans* stem canker in winter oilseed rape*. Plant Pathology* **29:**28-37.

Gladders P. 2009. Relevance of verticillium wilt (*Verticillium longisporum*) in winter oilseed rape in the UK. *Research Review No. 72.* HGCA, Stoneleigh.

Glen D M, Wiltshire C W, Milsom N F. 1984. Slugs and straw disposal in winter wheat. *1984 British Crop Protection Conference – Pests and Diseases* 139-144.

Glen D M. 2000. The effects of cultural measures on cereal pests and their role in integrated pest management. *Integrated Pest Management Reviews* **5**:25-40.

Glendining M J, Bradbury N J, Grace C A, Shen R, Brookes P C. 1994. The effects of long-term straw incorporation on the soil microbial biomass. *8th Nitrogen Workshop, Gwent*.

Glendining M J, Bradbury N J, Grace C A, Brookes P C. 2005. Short- and long-term effects of straw incorporation on soil N dynamics. *BSSS meeting, Soils 95, Sept*.

Granli T, Bøckman O. 1994. Nitrous oxide from agriculture. *Norwegian Journal of Agricultural Sciences, Supplement* **12**:1-128.

Gratwick M. 1992. *Crop pests in the UK*. Chapman & Hall, London.

Hassink, J. 1997 The capacity of soils to preserve organic C and N by their association with clay and silt particles. *Plant and Soil* **191**:77-87.

Hazarika S, Parkinson R, Bol R, Dixon L, Russel P, Donovan S, Allen D. 2009. Effect of tillage system and straw management on organic matter dynamics. *Agronomy for Sustainable Development* **29**:525-533.

HGCA. 1988. Changing Straw Disposal Practices. *Research Review 11.* HGCA, London.

HGCA. 2009. *Information Sheet 05: Assessing the nutrient content of cereal straw*. HGCA, London.

HGCA. 2013. *Topic Sheet 121: HGCA risk assessment for fusarium mycotoxins in wheat*. HGCA, Stoneleigh.

Hocking P J, Mason L. 1993. Accumulation, distribution and redistribution of dry matter and mineral nutrients in fruits of canola (oilseed rape), and the effects of nitrogen fertiliser and windrowing. *Australian Journal of Agricultural Research* **44**:1377-1388.

Hornby D. 1998. *Take-all disease of cereals: a regional perspective*. CAB International, Wallingford.

Houot S J, Molina A E, Chaussod R, Clapp C E. 1989. Simulation by NCSOIL of net mineralization in soils from the Deherain and 36 Parcelles fields at Grignon. *Soil Science Society of America Journal* **53**:451-455.

Janusauskaite D, Ciuberkis S. 2010. Effect of different soil tillage and organic fertilizers on winter triticale and spring barley stem base diseases. *Crop Protection* **29**:802-807.

Jarvis S C, Barraclough D, Unwin R G, Royle S M. 1989. Nitrate leaching from grazed grassland and after straw incorporation in arable soils. In: Management Systems to Reduce the Impact of Nitrates (Ed. J.J. German), Elsevier Applied Science, London, pp.110-125.

Jenkinson D. 1985. How straw incorporation affects the nitrogen cycle*. In : J. Hardcastle (ed.) Straw, Soils and Science.* AFRC, London.

Jenkinson D S. 1988. Soil organic matter and its dynamics. *In: Russell's Soil Conditions and Plant Growth (ed. A. Wild), pp. 564–607.* Longman Scientific and Technical, Harlow.

Jenkyn J F, Gutteridge R J, Jalaluddin M. 1994. Straw disposal and cereal diseases. *In: Ecology of Plant Pathogens, pp. 285–300. Eds J.P. Blakeman and B. Williamson.* Wallingford: CAB International.

Jenkyn J F, Gutteridge J, Todd A D. 1995. Effects of incorporating straw, using different cultivation systems, and of burning it, on diseases of winter barley. *Journal of Agricultural Science, Cambridge* **124**:195-204.

Jenkyn J F, Christian D G, Bacon E T G, Gutteridge R J, Todd A D. 2001. Effects of incorporating different amounts of straw on growth, diseases and yield of consecutive crops of winter wheat grown on contrasting soil types. *Journal of Agricultural Science, Cambridge* **136**:1-14

Jenkyn J F, Gutteridge R J, Bateman G L. 2004. Effects of cultivation method and crop debris on wheat stem-base diseases and take-all. In HGCA conference 2004: Managing soil and roots for profitable production.

Jenkyn J F, Gutteridge R J, Bateman G L, Jalaluddin M. 2010. Effects of crop debris and cultivations on the development of eyespot of wheat caused by *Oculimacula* spp. *Annals of Applied Biology* **156**:387-399.

Jensen L S, Mueller T, Magid J, Nielsen N E. 1997. Temporal variation of C and N mineralization, microbial biomass and extractable organic pools in soil after oilseed rape straw incorporation in the field. *Soil Biology and Biochemistry* **29**:1043-1055.

Jensen P K. 2009. Longevity of seeds of four annual grass and two dicotyledon weed species as related to placement in the soil and straw disposal technique. *Weed Research* **49**:592-601.

Johnston A E, Poulton P R, Coleman K. 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy* **101**:1-57.

Jordan V W L, Allen E C. 1984. Barley net blotch: influence of straw disposal and cultivation methods on inoculum potential, and on incidence and severity of autumn disease. *Plant Pathology* **33**:547-559.

Kanal A. (2002). Influence of different fertilization systems on the sulphur content of podzoluvisols and wheat grains. *Developments in Plant and Soil Sciences* **92**:854-855

Karami A, Homaeea M, Afzalinia S, Ruhipourc H, Basiratd S. 2012. Organic resource management: Impacts on soil aggregate stability and other soil physico-chemical properties. *Agriculture, Ecosystems and Environment* **148**:22-28.

Karhu K, Gärdenäs A I, Heikkinen J, Vanhala P, Tuomiad M, Liski J. 2012. Impacts of organic amendments on carbon stocks of an agricultural soil – Comparison of model-simulations to measurements. *Geoderma* 189-190:606-616.

Kendall D A, Chinn N B, Smith B D, Tidboald C, Winstone L, Western N M. 1991. Effects of straw disposal and tillage on spread of barley yellow dwarf virus in winter barley. *Annals of Applied Biology* **119**:359-364.

Kennedy T F, McDonald J G, Connery J, Purvis G. 2010. A comparison of the occurrence of aphids and barley yellow dwarf virus in minimum-till and conventional-till autumn-sown cereals. *Journal of Agricultural Science, Cambridge* **148**:407-419.

Kennedy T F, Connery J, Fortune T, Forristal D, Grant J. 2013. A comparison of the effects of minimum-till and conventional-till methods, with and without straw incorporation, on slugs, slug damage, earthworms and carabid beetles in autumn-sown cereals. *Journal of Agricultural Science* **151**:605-629.

Kilpatrick J. 2008. Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities. Report for NNFCC.

Kirchmann H, Persson J, Carlgren K. 1994. The Ultuna long-term soil organic matter experiment, 1956–1991. *Department of Soil Sciences, Reports and Dissertations 17. Swedish University of Agricultural Sciences, Uppsala, Sweden (55 pp.).*

Kretschmer, B., Allen, B., Kieve, D. and Smith, C. **2013**. *Shifting away from conventional biofuels: Sustainable alternatives for the use of biomass in the UK transport sector.* An IEEP discussion paper produced for ActionAid. Institute for European Environmental Policy (IEEP). London.

Kudsk P, Mathiassen S K. 2006. The influence of straw residues on herbicide activity. *NJF-Seminar 378. Tillage system for the benefit of agriculture and the environment.* http://www.vaxteko.nu/html/sll/njf/utredn_rapporter/NUR06-04/NUR06-04AM.PDF Accessed 3 July 2013.

Kudsk P, Mathiassen S K, Spliid N H. 2007. Non-inversion tillage affects herbicide activity. *14th EWRS Symposium, Hamar, Norway. pp 57.*

Kutcher H R, Malhi S S. 2010. Residue burning and tillage effects on diseases and yield of barley (*Hordeum vulgare*) and canola (*Brassica napus*). *Soil and Tillage Research* **109**:153-160.

Lafond G P, Stumborg M, Lemke R, May W E, Holzapfel C B, Campbell C A. 2009. Quantifying straw removal through baling and measuring the long-term impact on soil quality and wheat production. *Agronomy Journal* **101**:529-537.

Lemke R L, VandenBygaart A J, Campbell C A, Lafond G P, Grant B. 2010. Crop residue removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation experiment on a Udic Boroll. *Agriculture, Ecosystems and Environment* **135**:42-51.

Lenka N K, Lal R. 2013. Soil aggregation and greenhouse gas flux after 15 years of wheat straw and fertilizer management in a no-till system*. Soil and Tillage Research* **126**:78-89.

Limon-Ortega A, Govaerts B, Sayre K D. 2008. Crop rotation, wheat straw management, and chicken manure effects on soil quality. *Agronomy Journal* **101**:600-606

Loveland P, Webb J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. *Soil and Tillage Research* **70**:1-18.

Lutzow M Y, Kogel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G. 2006. Stabilisation of organic matter in temperate soils:mechanisms and their relevance under different soil conditions – a review. *European Journal of Soil Science* **57**:426-445.

MAFF. 1984. Straw Disposal and Utilisation: A Review of Knowledge

Machet J M, Mary B. 1989. Impact of agricultural practices on the residual nitrogen in soil and nitrate loss. In: *Management systems to reduce the impact of nitrates* (Ed. J.C. German), Elsevier Applied Science. London. Pp.126-146

Malhi S S, Lemke R, Wang Z H, Chhabra B S. 2006. Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil and Tillage Research* **90**:171-183.

Malhi S S, Lemke R. 2007. Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil and Tillage Research* **96**:269-283.

Malhi S S, Nyborg M, Solberg E D, Dyck M F, Puurveen D. 2011. Improving crop yield and N uptake with long-term straw retention in two contrasting soil types. *Field Crops Research* **124**:378-391.

Morris N L, Miller P C H, Orson J H, Froud-Williams R J. 2009. The effect of wheat straw residue on the emergence and early growth of sugar beet (*Beta vulgaris*) and oilseed rape (*Brassica napus*). *European Journal of Agronomy* **30**:151-162.

Morris N L, Miller P C H, Orson J H, Froud-Williams R J. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment - A review. *Soil and Tillage Research* **108**:1-15.

Mueller T, Jensen L S, Magid J, Nielsen N E. 1994. Turnover of nitrogen through the soil microbial biomass in a sandy loamd and a sandy soil (in situ) as affected by rape straw incorporation. In: Book of Abstracts from the 8th Nitrogen Workshop. 5-8 September, 1994. University of Ghent

Munkholm L J, Schjonning P, Debrosz K, Jensen H E, Christensen B T. 2002. Aggregate strength and mechanical behaviour of a sandy loam soil under long term fertilization treatments. *European Journal of Soil Science* **53**:129-137.

Nattrass, L, Smith, C Evans, G. 2011. *Advanced biofuels: The potential for a UK industry*. National Non-food Crop Centre (NNFCC): York.

Nicholson F A, Chambers B J, Mills A R, Strachan P J. 1997. Effects of repeated straw incorporation on crop fertiliser nitrogen requirements, soil mineral nitrogen and nitrate leaching losses. *Soil Use and Management* **36**:136-142.

Nix J. 2011. *John Nix farm management pocketbook. 42nd Edition 2012*. Agro Business Consultants, Melton Mowbray.

Nuttall W F, Bowren K E, Campbell C A. 1986. Crop residue management practices, and N-fertilizer and P-fertilizer eff ects on crop response and on some physical and chemical properties of a black Chernozem over 25 years in a continuous wheat rotation*. Canadian Journal of Soil Science* **66**:159-171.

Paulitz T C, Schroeder K L, Schillinger W F. 2010. Soilborne pathogens of cereals in an irrigated cropping system: Effects of tillage, residue management, and crop rotation. *Plant Disease* **94**:61-68.

Persson J, Mattson L. 1988. Soil C changes and size estimates of diff erent organic C fractions in a Swedish long-term small plot experiment. *Swedish Journal of Agricultural Research* **18**:9-12.

Powlson D S, Jenkinson D S, Pruden G, Johnston A E. 1985. The effect of straw incorporation on the uptake of nitrogen by winter wheat. *Journal of the Science of Food and Agriculture* **36**:26-30.

Powlson D S, Brookes P C, Christensen B T. 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. *Soil Biology and Biochemistry* **19**:159-164.

Powlson D S, Riche A B, Coleman K, Glendining M J, Whitmore A P. 2007. Carbon sequestration in European soils through straw incorporation: limitations and alternatives. *Waste Management* **28**:742-746

Powlson D S, Riche A B, Coleman K, Glendining M J, Whitmore A P. 2008. Carbon sequestration in European soils through straw incorporation: Limitations and alternatives. *Waste Management* **28**:741-746.

Powlson D S, Whitmore A P, Goulding K W T. 2011a. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Science* **62**:42-55.

Powlson D S, Glendining M J, Coleman K, Whitmore A P. 2011b. Implications for Soil Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agronomy Journal* **103**:279-287.

Powlson D S, Bhogal A, Chambers B J, Coleman K, Macdonald A J, Goulding K W T, Whitmore A P. 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agriculture Ecosystems and Environment* **146**:23-33.

PPDB. 2013. *The pesticide properties database*. http://sitem.herts.ac.uk/aeru/footprint/index2.htm Accessed 13/6/2013.

Prew R D, Ashby J E, Bacon E T G, Christian D G, Gutterdge R J, Jenkyn J F, Powell W, Todd A D. 1995. Effects of incorporating or burning straw, and of different cultivation systems, on winter wheat grown on two soil types, 1985–91. *Journal of Agricultural Science, Cambridge* **124**:173-194.

Procházková B, Málek J, Dovrtěl J. 2002. Effect of different straw management practices on yields of continuous spring barley. *Rostlinna Vyroba* **48**:27-32.

Rasmussen P E, Parton W J. 1994. Long-term effects of residue management in wheat fallow. Inputs, yields and soil organic matter. *Soil Science Society of America Journal* **58**:523-530.

Rice E L. 1984. *Allelopathy, second ed.* Academic Press, New York.

Robin D, Recous S, Mary B. 1994. Effect of initial residues composition on carbon and nitrogen dynamics during decomposition. In: Book of Abstracts from the 8th Nitrogen Workshop, 5-8 September, 1994. University of Ghent**.**

Rodgers-Gray B S, Shaw M W. 2000. Substantial reductions in winter wheat diseases caused by addition of straw but not manure to soil. *Plant Pathology* **49**:590-599.

Rodgers-Gray B S, Shaw M W. 2004. Effects of straw and silicon soil amendments on some foliar and stem-base diseases in pot-grown winter wheat. *Plant Pathology* **53**:733-740.

Saffigna P G, Powlson D S, Brookes P C, Thomas G A. 1989. Influence of sorghum residues and tillage on soil organic matter and soil microbial biomass in an Australian vertisol. *Soil Biology and Biochemistry* **21**:759-765.

Satsangi G P, Bartariya G, Saxena A. 2010. Allelopathic response of wheat (*Triticum aestivum* L.) straw on germination and growth of selected weed species*. 17th Australasian Weeds Conference, New Zealand* 147-149.

Schjonning P, Christensen B T, Carstensen B. 1994. Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. *European Journal of Soil Science* **45**:257-268.

Searcy E, Flynn P, Ghafoori E, Kumar A. 2007. The relative cost of biomass energy transport. *Applied Biochemistry and Biotechnology* **136-140**:639-652.

Shilling D G, Liebl R A, Worsham A D. 1985. Rye (*Secale cereale* L.) and wheat (*Triticum aestivum* L.) mulch: the suppression of certain broad-leaved weeds and the isolation and identification of phytotoxins. *In: The Science of Allelopathy pp.243-271. Eds A.R. Putnam and C.S. Tang. New York, USA. John Wiley and Sons Inc.*

Šidlauskas, Tarakanovas P. 2004. Factors affecting nitrogen concentration in spring oilseed rape (*Brassica napus* L.). Plant, Soil and Environment **50**:227-234.

Silgram M, Chambers B J. 2002. Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. *Journal of Agricultural Science, Cambridge* **139**:115-127.

Smith P, Powlson D S, Glendining M J, Smith J U. 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology* **3**:67-79.

Smith P, Powlson D S, Smith J U, Falloon P, Coleman K. 2000a. Meeting the UK's climate change commitments: options for carbon mitigation on agricultural and. *Soil Use and Management* 16:1-11.

Smith P, Goulding K W T, Smith K A, Powlson D S, Smith J U, Falloon P, Coleman K. 2000b. Including trace gas fluxes in estimates of the carbon mitigation potential of UK agricultural land. *Soil Use and Management* **16**:251-259.

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Pushpam K, McCarl B, Ogle S, O'Mara S, Rice C, Scholes B, Sirotenko O, Howden M, McAllister T, Pan G, Romanenkov V, Schneider U, Towprayoon S, Wattenbach M, Smith J. 2008. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B.* **363**.

Sommer R, Ryan J, Masri S, Singh M, Diekmann J. 2011. Effect of shallow tillage, moldboard plowing, straw management and compost addition on soil organic matter and nitrogen in a dryland barley/wheat-vetch rotation. *Soil and Tillage Research* **115-116**:39-46.

Steinsiek J W, Oliver L R, Collins F C. 1982. Allelopathic potential of wheat (*Triticum aestivum*) straw on selected weed species. *Weed Science* **30**:495-497.

Stenberg M, Aronsson H, Linden B, Rydberg T, Gustafson A. 1999. Soil mineral nitrogen and nitrate leaching losses in soil tillage systems combined with a catch crop. *Soil and Tillage Research* **50**:115-125.

Stewart B A, Porter L K, Viets F G. 1966. Effect of sulfur content of straws on rates of decomposition and plant growth. *Soil Science Society of America Journal* **30**:355-358

Stoddart H, Watts J. 2012. *Energy potential from UK arable agriculture: straw – what is it good for?* HGCA, Stoneleigh.

Summerell B A, Burgess L W. 1988. Stubble management practices and the survival of *Fusarium graminearum* Group 1 in wheat stubble residues. *Australasian Plant Pathology* **17**:88-93.

Summerell B A, Burgess L W. 1989. Factors influencing survival of *Pyrenophora tritici-repentis*: stubble management. *Mycological Research* **93**:38-40.

Swan L J, Backhouse D, Burgess L W. 2000. Surface soil moisture and stubble management practice effects on the progress of infection of wheat by *Fusarium pseudograminearum*. *Australian Journal of Experimental Agriculture* **40**:693-698.

Symondson W O C, Glen D M, Wiltshire C W, Langdon C J, Liddell J E. 1996. Effects of cultivation techniques and methods of straw disposal on predation by *Pterostichus melanarius* (Coleoptera: Carabidae) upon slugs (Gastropoda: Pulmonata) in an arable field. *Journal of Applied Ecology* **33**:741-753.

Thomsen I K. 1993. Turnover of 15N-straw and NH4NO3 in a sandy loam soil: Effects of straw disposal and N fertilization. *Soil Biology and Biochemistry* **11**:1561-1566

Turkington T K, Clayton G W, Woods D L. 2000. The impact of soil incorporation of canola residues and stubble application of chemicals on decomposition and inoculum production by *Leptosphaeria maculans*. *Canadian Journal of Plant Pathology* **22**:155-159.

Turley D B, Phillips M C, Johnson P, Jones A E, Chambers B. 2003. Long-term straw management effects on yields of sequential wheat (*Triticum aestivum* L.) crops in clay and silty clay loam soils in England. *Soil and Tillage Research* **71**:59-69.

van Groenigen K J, Hastings A, Forristal D, Roth B, Jones M, Smith P. 2011. Soil C storage as affected by tillage and straw management: an assessment using field measurements and model predictions. *Agriculture, Ecosystems and Environment* **140**:218–225

Verhulst N, Govaerts B, Nelissen V, Sayre K D, Crossa J, Raes D, Deckers J. 2011. The effect of tillage, crop rotation and residue management on maize and wheat growth and development evaluated with an optical sensor. *Field Crops Research* **120**:58-67.

Wahmhoff W, Hedke K, Tiedemann A V, Nitzsche O, Ulber B. 1999. Zum einfluss von fruchtfolge und bodenbearbeitung auf die entwicklung wichtiger schaderreger des winterrapses | [Impact of crop rotation and soil cultivation on the development of pests and diseases of rapeseed]. *Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz* **106**:57-73.

Water UK 2010. *Recycling of Biosolids to Agricultural Land*. Issue number 3, January 2010. Water UK 1 Queen Anne's Gate, London.

Watts C W, Clark L J, Poulton P R, Powlson D S, Whitmore A P. 2006. The role of clay, organic carbon and long-term management on mouldboard plough draught measured on the Broadbalk wheat experiment at Rothamsted. *Soil Use and Management* **22**:334-341.

Welham S J, Turner J A, Gladders P, Fitt B D L, Evans N, Baierl A. 2004. Predicting light leaf spot (*Pyrenopeziza brassicae*) risk on winter oilseed rape (*Brassica napus*) in England and Wales, using survey, weather and crop information. *Plant Pathology* **53**:713-724.

Webb J, Loveland P J, Chambers B J, Mitchell R, Garwood T. 2001. The impact of modern farming practices on soil fertility and quality in England and Wales. *Journal of Agricultural Science, Cambridge*, **137**, 127-138.

West J S, Kharbanda P D, Barbetti M J, Fitt B D L. 2001. Epidemiology and management of *Leptosphaeria maculans* (phoma stem canker) on oilseed rape in Australia, Canada and Europe. *Plant Pathology* **50**: 10-27.

Wildermuth G B, Thomas G A, Radord B J, McNamara R B, Kelly A. 1997. Crown rot and common root rot in wheat grown under different tillage and stubble treatments in southern Queensland, Australia. *Soil and Tillage Research* **44**:211-224.

Williams A G, Audsley E, Sandars D L. 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities*. Defra Project Report IS0205*. Bedford: Cranfield University and Defra.

Withers P J A. 1991. Removal of phosphorus and potassium from the soil in wheat and barley straw. *Journal of Agricultural Science, Cambridge* **117**:221-224.

WRAP. 2011. *A Study of the UK Organics Recycling Industry in 2009*. http://www.organics-recycling.org.uk/dmdocuments/2009_Organics_Report_Final.pdf [accessed 8/12/11].

Wu H, Pratley J, Lemerle D, Haig T. 2001. Allelopathy in wheat (*Triticum aestivum*). *Annals of Applied Biology* **139**:1-9.

Appendix 1: Straw production, use and price

A1. Straw production

There is no robust survey data on total straw production in Great Britain (GB). However, a number of studies (Copeland & Turley, 2008; Kilpatrick, 2008; Stoddart & Watts, 2012) have reviewed production and utilisation based on crop areas and harvest indices, while ADAS collate annual regional estimates of yields and production based on agronomist information. Reported values for GB annual straw production range from 11.9 Mt to 13.9 Mt, with the variations due to slight differences in assumptions and crops areas (Table A1).

Table A1. Previous reported values for straw production and utilisation in Great Britain (kt/yr)

	Copeland & Turley (2008)	Kilpatrick, (2008)	Stoddart & Watts (2012)
Production (cereal and oilseeds)*	**11,900**	**13,900**	**12,200**
Utilisation (total)	**6,240**	**-**	**6,170**
Animal bedding	6,200	5,800	5,800
Carrots (over-wintering)	-	-	250
Mushroom compost	40	-	40
Export	-	-	80
Surplus before bioenergy	**5,660**	**-**	**6,030**
Bioenergy	487	-	300
	(Use at Ely, Brigg, Goole, Holderness and Sleaford plants)		(Use at Ely and Drax plants)

*Potentially removable straw

ADAS provide GB straw production figures for Defra based on regional estimates of actual straw yield and crop area, rather than standard harvest indices, although the straw yields are not based on a statistical survey or actual measurements so can only be considered as a guide. These reports show large within year variations depending on soil type, local weather and crop management, with wheat straw yields typically 2.8-3.9 t/ha, although the range between 2008 and 2012 was 2.0 - 5.3 t/ha.

The total potentially removable GB straw production of the main cereals and OSR was *c.*11.0 Mt based on 2012 crop areas and 5-year average yields, with OSR straw accounting for 11% of the total (Table A2).

Table A2. UK straw production estimates (ADAS regional information over 5 years)

	2012 Area (ha)	Five year average straw yield (t/ha)	Potentially removable straw (Mt)	Percentage of total straw production (%)
Wheat	1,950,000	3.4	6.63	62%
Winter barley	380,000	2.8	1.06	10%
Spring barley	600,000	2.5	1.50	14%
Oats	120,000	3	0.36	3%
Oilseed rape	650,000	1.8	1.17	11%
Total*			10.72	100%

*Not including straw from other minor cereals

A2. Straw utilisation

Straw is mainly used for animal bedding, horticulture and bioenergy, with some export potential in some years. There is no official data available for straw usage in animal bedding, however estimates range between 5.8Mt (UK, Stoddart & Watts, 2012) and 6.24 Mt (GB, Copeland & Turley, 2008). A recent unpublished ADAS analysis for Great Britain, estimated that straw usage across all livestock sectors and horticulture was over 8 Mt (68% of total production). In addition, at least 0.3 Mt/yr was used for bioenergy, with the potential to expand (Stoddart & Watts, 2012).

A3. Straw supply and demand

The data in Table A1 suggest that there is sufficient straw for all uses, with a surplus (before bioenergy use) of *c*.5-6Mt, which is mostly wheat straw.

Where livestock numbers are high and the arable area limited, then straw prices tend to be high and straw is mostly baled. In predominantly arable areas with low livestock numbers or few alternative outlets for straw, its price is low and straw tends to be chopped and incorporated, although there are local effects such as demand from biomass burning power plants such as Ely or Drax. This regional variation is shown in Table A3, where the proportion of wheat straw removed in 2012 varies from 45% in the East Midlands to 97% in Wales, averaging 64% for Great Britain as a whole. There is also variability between years; when straw yields are low (e.g. 2010 and 2011) the proportion baled tends to increase (to 68% for GB in these years); when straw yields are high, the proportion removed tends to be lower (e.g. 41% in 2008 and 56% in 2012 for Great Britain).

Barley straw is more in demand than wheat straw from the livestock sector as it is regarded as a better feedstuff for ruminants and a better bedding material for pigs. Thus a higher proportion of barley straw is baled (typically 90 -100%). Removal of OSR straw is much less common than cereal straw, nevertheless an estimated 18% of OSR straw is typically baled in Great Britain with similar regional differences to cereal straw (Table A4).

Table A3. Estimated average regional wheat straw production and prices 2010-2012.

Region	Crop area baled (ha)	Estimated straw yield* (t/ha)	Percentage removed by baling*	Straw price (£/ha)**	Straw price (£/t delivered)**
North East	59,000	4.00	90	71.23	63.60
North West	31,000	3.29	91	117.10	63.75
Yorks & Humber	137,000	3.58	55	57.50	56.75
East Midlands	164,000	3.58	45	41.00	41.60
West Midlands	140,000	3.70	85	109.20	62.40
Eastern	266,000	3.40	53	68.00	75.00
South West	139,000	3.56	69	86.00	56.00
South East	128,000	3.47	64	87.60	59.80
Wales	21,000	3.59	97	131.60	75.40
Scotland	84,000	4.25	81	108.25	90.00
Great Britain (total or average)	1,170,000	3.58	64	76.88	60.85

Source: unpublished ADAS data (not derived from a full stratified survey.
* Based on regional agronomist reports of typical straw yields and % total area baled averaged over 3 years
** Based on regional information at harvest

Table A4. Estimated average oilseed rape straw production and prices 2010-2012.

Region	Crop area baled (ha)	Estimated straw yield* (t/ha)	Proportion removed by baling*	Straw price (£/ha)**	Straw price (£/t delivered)**
North East	15262	2.95	60	25.00	-
North West	1974	2.30	37	50.00	-
Yorks & Humber	16093	2.91	18	31.25	-
East Midlands	18918	2.53	12	40.33	31.67
West Midlands	9333	2.01	18	18.50	9.33
Eastern	37329	2.91	25	37.00	-
South West	3571	3.04	5	33.33	43.33
South East	5127	2.94	8	20.00	-
Wales	3153	1.98	77	35.00	32.50
Scotland	8329	2.65	23	50.00	-
Great Britain (total or average)	119089	2.72	17	28.01	26.60

Source: unpublished ADAS data (not derived from a full stratified survey.
* Based on regional agronomist reports of typical straw yields and % total area baled averaged over 3 years
** Based on regional information at harvest

Based on unpublished ADAS annual data, in a typical year with average yields the estimated straw removal was estimated to be 7.3 Mt, of which the majority was cereal straw, with a typical surplus of 3.4 Mt (Table A5.

Table A5. Estimates of straw removal to meet market demand and surplus

	Potentially removable straw (Mt)	Average % baled	Estimated straw removal (Mt)	Surplus (Mt)
Wheat	6.63	68	4.51	2.12
Winter barley	1.06	90	0.96	0.10
Spring barley	1.50	90	1.35	0.15

Oats	0.36	80	0.29	0.07
Oilseed rape	1.17	18	0.21	0.96
Total	10.70	68	7.31	3.40

Source: unpublished ADAS data (not derived from a full stratified survey.

Analysis of the unpublished ADAS annual data suggests that in general the market for baled straw operates effectively, with years of anticipated shortage due to low yields or low crop area resulting in higher prices and an increased in baled area as a response. Shortages can be very localised with transport costs the main barrier. There are some instances of imports from northern France in years of low production, as well as exports in years of higher production.

A4. Market price of straw

The total value of straw utilised in the UK was estimated to be £372 million (Defra, 2011), which equates to an average value of £51/t (based on 7.3 Mt removed; Table A2).

The market value of straw varies depending on the type of straw, when it is purchased, location and local demand. It is further complicated by local agreements where straw is sold in return for manure, or where long-standing agreements result in non-market prices. Similarly, prices vary during the season and between seasons depending on local demand from the livestock sector and local supply of straw, grass, hay and forage.

The main types of agreement for straw sales are i) straw baled for own use; ii) in swath for baling and collection (usually priced in £/ha by local treaty), iii) baled for collection (usually sold per bale or per tonne); iv) baled and delivered, often through a third party merchant (usually sold per bale or per tonne); v) straw auctions

Straw for on farm use

Valuing straw for on-farm use can be done by an internal transfer between enterprises either at a typical market value or at cost (accounting for the value of nutrients removed, and baling and transportation costs).

In swath for baling

Many arable farmers have agreements with local livestock farmers or straw contractors who purchase the straw in the swath and are responsible for baling and removing the straw. Prices are agreed by private treaty and vary greatly with some long standing agreements at below the market rate, and many at a similar rate year to year independent of market fluctuations. In these cases, straw is usually sold by the hectare. Yields will vary depending on crop quality and decisions made by the combine harvester driver on cutting height, with prices varying accordingly. Average prices at harvest from 2010 to 2012 (including a low straw yield in 2011 and a high straw yield in 2012) ranged from £18-£50/ha (unpublished ADAS data collected at harvest – not a statistical survey).

Baled for collection (ex farm prices) or delivered

Some farmers prefer to manage the straw baling themselves to ensure there are no delays in clearing fields. Straw is baled and stored on the farm and is collected by farmers or sold through merchants. Ex-farm prices vary depending on the type of straw and when it is sold. Farmers Weekly publish weekly prices of hay, barley straw and wheat straw from the British Hay & Straw Merchants Association (Figure 1).

HAY AND STRAW w/e 9 February 2014

Prices supplied by British Hay & Straw Merchants' Association
Merchants' buying prices in £/tonne ex-farm

Area	Pick-up Baled Seed Hay	Pick-up Baled Meadow Hay	Big Bale Hay	Pick-up Baled Barley Straw	Pick-up Baled Wheat Straw	Big Sq Baled Barley Straw	Big Sq Baled Wheat Straw
North East	100	80	75	70	-	60	50
East Yorks	-	85	65	-	-	53	46
N Midlands	90	90	70	70	-	55	45
E Midlands	-	-	72	-	-	52	45
C Midlands	120	100	70	-	-	50	40
E Counties	125	95	75	67	58	52	42
South east	120	80	60	70	65	50	38
South	-	94	74	-	-	56	41
South West	125	100	80	70	70	57	50
South Wales	120	100	75	75	-	55	50
SE Scotland	-		115	-	-	65	55

Trade Comment: Steady trade this week

Figure 2. Example of straw prices at 9 February 2014 from Farmers Weekly.

Delivered prices at harvest from 2010 to 2012 ranged from £41/t in East Midlands to £90/t in Scotland (unpublished ADAS data collected at harvest – not a statistical survey), but will depend on local availability and transport costs.