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# Agronomic, economic and environmental analysis of dual-purpose wheat cultivars for bioenergy

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## 1. Abstract

Concerns about climate change and energy supply security have led to a focus on using biofuels to replace oil-based fuels in the transport sector. Second generation biofuels (SGBs), which are produced from lignocellulosic material such as wheat straw, are currently being developed.

This project investigated wheat straw supply for SGB production, focusing on the use of dual-purpose cultivars (DPCs) that are optimised to provide for both food and SGB markets. The project consisted of: agronomic assessment of cultivars and management practices for traits associated with a DPC; economic assessment of the value of these DPCs to farmers and costs of straw delivery; life cycle assessment for quantifying environmental burdens associated with straw production from DPCs; and a farmer survey for quantifying current straw supply and potential future straw supply should a new market for straw emerge.

Agronomic trials did not identify any outstanding candidates for use as DPCs from currently grown wheat cultivars or any management practices that would benefit DPC traits. Economic assessment found that straw production costs were lower than the straw price but the overall straw gross margins were much lower than grain gross margins suggesting that grain yield would not be traded off against increased straw yield. Transport costs across the biomass supply chain were slightly lower with the use of DPCs. Environmental burdens for straw production were found to be lower than in other studies but the allocation process had a large influence on the outcomes for this measure. From the survey, 50% of respondents were willing to increase straw yields but even with a very generous price of straw, 21% of respondents would not supply additional straw. The work suggests that straw availability is lower than some current estimates and there is only limited scope to increase straw yield through cultivar selection.

## 2. Introduction

There is worldwide effort to reduce fossil fuel consumption due to concerns about anthropogenic climate change and energy security (IPCC, 2007; van Vuuren et al., 2012). This reduction can be achieved through the replacement of fossil fuels with alternative energy sources. Developing clean energy technologies for the transport sector is seen as vitally important because of its large share of oil consumption and greenhouse gas (GHG) emissions; for example, in the European Union, the transport sector has a 94% dependency on oil (European Commission, 2013). Biofuels, which are liquid or gaseous fuels predominantly produced from biomass (Demirbas, 2008), are being used to replace some of the fossil fuel used in the transport sector. In general, biofuels have lower GHG emissions than fossil fuels and are seen as a major technology for the mitigation of anthropogenic climate change (Borrion et al., 2012a; Cherubini & Strømman, 2011).

There are a number of biofuel types and production methods but they can be broadly be classified as first generation biofuels (FGBs) and second generation biofuels (SGBs). FGBs are produced from edible plant material such as wheat grain. Currently the production of biofuels is almost entirely reliant on FGB feedstock. However, the use of edible biomass as feedstock has led to a number of environmental and social concerns (Gnansounou, 2010), such as competition with food production, which is believed to have contributed to increased food prices (Mitchell, 2008). Another concern is indirect land-use change, which is where the use of farmland for biofuel feedstock production has necessitated the expansion of agricultural land to maintain food production levels (Kim & Dale, 2011); this is particularly environmentally harmful when the land being converted is forest. These environmental concerns have encouraged the development of SGBs.

SGBs, also known as cellulosic biofuels or lignocellulosic biofuels, are produced from lignocellulosic material, such as the non-food parts of crops, forestry residue, dedicated energy crops (e.g. miscanthus) and waste material (Gnansounou, 2010). There has been significant investment in the development of these biofuels and the results of this investment are being realised with commencement of commercial-scale production at the Crescentino Plant in Italy (AEC, 2013).

Wheat straw is one possible feedstock for cellulosic biofuel production. In the UK a significant proportion of wheat straw is chopped and incorporated into the soil after grain harvest (Copeland & Turley, 2008; Glithero et al., 2013b) offering a potential resource for biofuel production. To complement research into improving feedstock-to-biofuel conversion technologies, research is also required to investigate feedstock production and sourcing, and the associated environmental and economic consequences.

Wheat straw has low value and plant breeding efforts have focused on increasing grain yield. These increases in grain yield have come at the expense of reduced straw yields (Austin et al., 1980). Among high-yielding modern cultivars there is variation is straw yields (Larsen et al., 2012) suggesting that cultivars can be selected with high straw and grain yields. It may be possible to select cultivars from among currently grown cultivars or breed cultivars with higher straw yields. These cultivars could be considered dual-purpose cultivars (DPCs) with grain for human consumption or animal feed and straw for bioenergy. The feasibility of the use of DPCs will depend on whether they exist among currently produced cultivars or can be bred through conventional breeding programmes. It will also depend on whether there is a market for these cultivars and that will require benefits of growing these cultivars over cultivars that are optimised for grain alone.

## 2.1. Cultivar traits

A potential ideotype of DPC has four key traits: high grain yield; high straw yield; good straw digestibility (i.e. the ease at which the straw is broken down to be converted into biofuel); and good lodging resistance. In this literature review these traits will be discussed but as grain yield has been the focus for crop breeding and management it will not be considered individually but instead will be considered in terms of its relationship with the other key traits.

### 2.2.1 Straw

Comparing cultivars based on straw yield is difficult as straw yield is rarely quantified (Larsen et al., 2012). There are two reasons for this: firstly, straw is seen as a by-product to the more important grain, with its value being much lower, so there is less incentive for it to be quantified; secondly, straw yields are more difficult to quantify than grain yields, particularly on trial plots, due to straw losses and movement between combining and baling, and this discourages straw yields from being quantified. There is limited research considering environmental and genetic determinants of straw yield though knowledge does exist within the farming community (i.e. anecdotal). In order to select cultivars for use as DPCs, an understanding of variation in straw yields is required including the quantification of straw yields for cultivars.

Straw yields vary with cultivar (Donaldson et al., 2001; Engel et al., 2003; Skøtt, 2011; Larsen et al., 2012). Cultivar variation is most obvious when comparing modern cultivars with older cultivars as straw yields have decreased over the past 100 years with the development of semi-dwarf cultivars (Austin et al., 1980; Shearman et al., 2005). However, even amongst modern cultivars there is variation in straw yield (Larsen et al., 2012); though in a comparison of modern cultivars Roy (2014) did not find a significant difference between cultivars. It has been suggested that increasing straw yield could involve the selection of older and non-commercial cultivars (Larsen et al., 2012); however, these have lower grain yields and are more prone to lodging (Austin et al., 1980). It is, therefore, more realistic to find cultivars within those that are currently grown for use as a DPC, or to factor straw yield into future cultivar breeding programmes.

In general, straw yields in the UK range from 2.5 to 5 t $ha^{-1}$ (ABC, 2013; Nix, 2013). However, there is considerable variation. Glithero et al. (2013a) estimated the harvestable straw yields in England from the numbers and types of bales being produced; regional averages ranged from 1.66 t $ha^{-1}$ to 3.34 t $ha^{-1}$. The average straw yield of suppliers for Ely straw-fired power station is 5 t $ha^{-1}$ (Newman, 2003). The values in Glithero et al. (2013a) are lower than those given in ABC (2013) and Newman (2003); however, Glithero et al.'s results are for the 2010 crop harvest, when dry weather may have led to low straw yields throughout England (Anon, 2010).

Published values of straw yields for individual wheat cultivars in the UK are not included in current wheat Recommended Lists (RLs) and there do not appear to be any sources available for straw yield data for UK cultivars. There are values available for barley straw yields from the Agri-Food and Biosciences Institute (AFBI), where each cultivar is placed in one of four categories (from low to very high; Anon, 2013a). Given inclusion of straw production groupings within the RLs for barley, it is feasible that if a stronger market for wheat straw develops there may be an interest in including straw yield metrics in future wheat RLs.

#### 2.2.1.4 Grain and straw yields relationship

The relationship between grain and straw yields is important when considering the optimal characteristics of a DPC. The relationship is seen when we consider the breeding of cultivars; in the UK, whilst straw yields have decreased over the past 100 years, grain yields have increased (Austin et al., 1980; Shearman et al., 2005). Grain yields have increased due to increases in both above ground dry matter (AGDM) and harvest index (HI), which is the ratio of grain yield to AGDM. Increasing HI has resulted from greater partitioning of resources to the grain at the expense of the straw. After 1983, the increases in grain yield have mainly been the result of increases in AGDM (Shearman et al., 2005).

Selecting older cultivars as DPCs for their higher straw yields would result in lower grain yields so would be unlikely to be commercially viable. It has been suggested that there is an upper limit to HI of 0.62 (Austin et al., 1980); as cultivars have nearly reached this limit, any future increases in grain yield will require an increase in AGDM (Shearman et al., 2005). This suggests that attempts to increase grain yield further will result in straw yields increasing.

### 2.2.2 Lodging

Lodging is defined as the state of permanent displacement of cereal stems from their upright position. It can cause grain yield and quality losses, as well as greater harvesting costs thus farmers seek to minimise lodging through crop management and cultivar selection (Berry et al., 2004). The interaction between lodging, cultivar choice and agronomic practices, which are described below, suggest that there may be relationships between lodging risk and traits that are beneficial to a DPC, such as straw yield and digestibility. Although lodging susceptibility has been extensively studied (see Berry et al., 2004, for a comprehensive review of lodging in cereals), only brief consideration has been given to the interactions between lodging susceptibility and the traits for improved cellulosic biofuel production.

The plant structure influences the likelihood that a plant will lodge (Berry et al., 2004). In modelling the failure wind speed of wheat (i.e. the minimum wind speed that is likely to cause lodging in a particular plant at a particular time), Baker et al. (1998) modelled the bending moment (also known as the leverage force), calculated from the height at the centre of gravity (HCG) of the plant, the natural frequency and the drag of the plant based on the ear area. The strength of the stem base is based on the stem material strength, which is determined by the breaking strength of the stem, internode length, and the stem radius and wall width of the lower internodes. The root-soil interface strength is based on the root plate spread and depth. The model calculates the wind speed at which lodging will occur; with the stem failure wind speed (SFWS) and root failure wind speed (RFWS) the wind speeds at which stem lodging and root lodging will occur, respectively.

Genetic and environmental factors affect lodging susceptibility through their influence on plant form. Cultivars vary in their structural characteristics (e.g. height, HCG) and, therefore, influence lodging susceptibility. Berry et al. (2003a) found that for a selection of 15 cultivars SFWS ranged from 9.79 m $s^{-1}$ to 12.71 m $s^{-1}$ and RFWS ranged from 7.15 m $s^{-1}$ to 11.81 m $s^{-1}$.
There are multiple strategies for minimising lodging risk. As lodging risk varies between cultivars (Berry et al., 2003a) farmers can choose to grow cultivars that have higher lodging resistance. Lodging susceptibility is one of the major criteria used for cultivar selection and data is provided for lodging resistance on the Recommended Lists (e.g. AHDB RLs). These ratings are based on visual scoring of lodging (RL Project Consortium, 2014); however, this approach has been criticised because of limitations, such as being dependent on lodging events occurring during the assessment years to compare cultivars (e.g. Berry et al., 2003b).

Management practices can be used to reduce lodging susceptibility. These include reducing seed rate, delaying sowing, reducing and delaying nitrogen (N) application, and rolling the soil (Berry et al., 2007). The most common method for reducing lodging is the application of plant growth regulators (PGRs; Berry et al., 2007). They achieve this through reducing cell elongation and decreasing cell division, and can reduce plant height by 40% (Berry et al., 2004). In the UK, PGRs were applied to 88% of the winter wheat area in 2010 (Garthwaite et al., 2011). The most widely used was chlormequat, which works through blocking the early steps of gibberellic metabolism

(Rademacher, 2000). Berry et al. (2003a) found that the application of a split of chlormequat at growth stages (GSs) 30 and 31 reduced both SFWS and RFWS by 1.4 m $s^{-1}$. PGR application can lead to a reduction in the area lodged by anything up to 70% (Berry et al., 2004). However, Roy (2014) found that chlormequat application did not significantly influence lodging susceptibility for 15 cultivars, though there was a general trend of increased SFWS.

### 2.2.3 Wheat straw digestibility

During the production of SGBs, it will not be economical to convert all the cellulose into biofuel. Therefore, the ethanol yield of straw depends not only on the total sugars present in the material but also the ease at which these sugars are made accessible to fermentation. *Digestibility*, also referred to as *degradability* and *saccharification potential*, refers to the amount of a defined sugar released from a feedstock under specific processing conditions.

Currently, research is investigating the engineering of lignocellulosic material with increased digestibility through methods such as transgenic technologies (de Leon & Coors, 2008; Phitsuwan et al., 2013). Other work, including this project, is investigating current cultivar variability and the application of these cultivar differences to the production of biofuels (e.g. Lindedam et al., 2012).

Feedstock digestibility of currently grown cultivars has been researched extensively, though the majority of this work has considered it from an animal nutrition perspective or for other uses, such as mushroom production. These studies varied in the methods used for assessment but they were all considering the breakdown of lignocellulosic material. Some studies used assays to quantify the amount of sugar released whilst other studies assessed the loss of mass during the *in sacco* incubation of lignocellulosic material. Work in wheat found that digestibility varies with cultivar (e.g. Knapp et al., 1983; Kernan et al., 1984; Capper, 1988; Habib et al., 1995) and environmental conditions (Tolera et al., 2008) but it is unclear the relative importance of genotype and the environment. In barley, Capper (1988) suggested that digestibility was more strongly influenced by genotype than environment; however, Wright & Hughes (1989) found digestibility differed as much between trial sites as between cultivars.

Several studies have compared the digestibility between wheat cultivars for the purpose of identifying cultivars for use as feedstock for biofuel production. Some studies have found significant differences in the digestibility of wheat cultivars (e.g. Lindedam et al., 2010; Jenson et al., 2011; Lindedam et al., 2012) whilst other studies have not found significant differences (e.g. Larsen et al., 2012; Roy, 2014). Based on differences between cultivars and locations, Jensen et al. (2011) and Lindedam et al. (2012) found that there was a certain amount of heritability in digestibility. This means that differences were not just related to management practices and cultivars can be selected based on their potential digestibility.

It has been hypothesised that digestibility is linked to the lodging susceptibility of cereals. Specifically, it has been suggested that greater straw stiffness could be due to modified anatomical features of the stem, which may decrease digestibility of the straw. Travis et al. (1996) compared the basal internode digestibilities of a wheat cultivar susceptible to lodging with a cultivar with good lodging resistance and found that the digestibility was higher for the lodging susceptible cultivar. Lindedam et al. (2010) suggest that the low digestibility of one cultivar resulted from it having stiff straw. However, Ramanzin et al. (1991) did not find a relationship between lodging and digestibility.

Another aspect determining lodging susceptibility is plant height though it is unclear if plant height is related to digestibility. If digestibility does increase with plant height as Lindedam et al. (2012) suggest then this would lead to a potential trade-off between good lodging resistance and having higher digestibility. But Jensen et al. (2011) and Roy (2014) found the opposite relationship between plant height and digestibility and, therefore, supports that there is no trade-off between the two traits. Roy (2014) compared digestibility to multiple plant traits responsible for lodging susceptibility; for most traits there was no relationship but for some traits there was a weak relationship with digestibility, such as a negative relationship with stem material strength. However, digestibility was not related to failure wind speeds. If there is a link between height and digestibility then this could indicate a relationship between digestibility and straw yield, as height is correlated with straw yield. It does not appear that the digestibility of cereal crops has been compared to straw yields. Thus, it is unclear whether there is a trade-off between the two.

### 2.2. Potential benefits

Whether there is interest in growing DPCs will depend on the extent of benefits they can provide to stakeholders within the biomass supply chain. There are a number of potential areas where the use of DPCs may provide benefits.

#### 2.2.1. The economic value of dual-purpose cultivars

Before a farmer sells the straw, the price of straw must cover the costs of its collection in the form of baling and on-farm transport, as well as other associated costs, including nutrient loss from not incorporating straw. Determining the straw value requires consideration of many factors (Aden et al., 2002). Some are quantifiable, such as fertilisers to replace the nutrients removed from the field in the straw, whilst others, such as long-term impacts on soil characteristics and the effects on yields of subsequent crops, are much harder to quantify. These factors are highly dependent on local conditions and, therefore, estimates of straw value have varied greatly between studies (Carriquiry et al. 2011). As well as these costs, the price of straw needs to cover the profit a farmer would expect to cover the additional management effort and planning required to bale and remove straw (Aden et al., 2002).

Estimates for the cost of lignocellulosic feedstock have been made. These values tend to be highly variable due to aspects such as considerable uncertainty in estimates for fertiliser costs and farmer premiums (Aden et al., 2002). Carriquiry et al. (2011) reviewed cost estimates of US lignocellulosic material delivered to a biorefinery and found a range of \$19–84 $t^{-1}$. These estimates varied due to which costs were included in the calculations, feedstock yields, transport distances, storage options, and the prices of these. The fertilisers included varied, whilst some did not consider storage and others did not include a premium to farmers, assuming that the feedstock would be sold at breakeven price (e.g. Gallagher et al., 2003). There was also wide variation in the costs of the various operations and whether to include credits for not carrying out specific operations (e.g. not having to chop straw when it is baled).

The question of whether to bale or chop straw is routinely addressed in the publication *Farmers Weekly*; it appears that farmers are often uncertain of whether to bale or chop due to conflicting information. Knowing a minimum value of straw would benefit farmers. ADAS (2008) estimated that a price of £31.84 oven dry $tonne^{-1}$ would be required to cover costs of fertiliser and contractors. However, they suggest a price of £47.76 $odt^{-1}$ as they include a 50% premium to cover value of other nutrients, the loss of soil structural benefits, as well as profit margin to cover the time and effort involved. This is much higher than Banham (2011), who estimated a price of £22.58–23.37 $t^{-1}$ based on fertiliser and contractors fees. However, this lower value is partly a result of a reduction in fertiliser prices between when the studies took place, as well as Banham (2011) not including N fertiliser in the calculations and assuming lower estimated contractor fees. Newman (2003) estimated a straw price of £30.08 $t^{-1}$. This consisted of a farmer payment of £3.00 $t^{-1}$, collections costs of £23.98 $t^{-1}$, a loss factor and a price for overheads and costs. A price for the replacement nutrients is not given, which suggests these are supposed to be covered by the payment to the farmer. The costs for collecting the straw included a cost for combining, which other estimates do not include. The loss factor, which is an allowance for the loss of material from degradation in the field and inclement weather, disrupting supply, is also not included in other studies.

These values demonstrate the variability in cost estimates and the difficulty farmers have in making decisions on whether to bale straw. Each estimate was based on different ranges of factors. The value for ADAS (2008) is considerably higher than the other values but this does include a premium for the hard-to-quantify impacts. These breakeven prices need to be compared to the price farmers need to be offered before they sell their straw; Glithero et al. (2013b) found that farmers wanted on average £50 $t^{-1}$ for their straw. There is need for an accurate valuation of wheat straw to enable the economic benefit of DPCs to be quantified.

### 2.2.2. Straw transport costs

Crop residue biomass is characterised by low bulk density (McKendry, 2002), low calorific content (Allen et al., 1996) and variable moisture contents (Sokhansanj et al., 2006). Residue supply is widely distributed (Caputo et al., 2005), highly variable in yield (Mabee et al., 2006), and there is demand throughout the year but seasonal feedstock production, often with only a short time window for collection due to competition with other harvesting and land preparation operations (Sokhansanj et al., 2006). In comparison to the majority of haulage operations, the biomass delivery chain has an empty outward load (Rentizelas et al. 2009). Due to the low calorific value and low bulk density of feedstocks, the supply system is typified by a large number of truck deliveries relative to energy delivery for fossil fuels (Allen et al., 1996). Because of this, the transportation of feedstock is responsible for a large proportion of costs.

Transportation costs are extremely important in the economic feasibility of SGB production (Kaylen et al., 2000). In previous studies, the transportation costs have been found to represent between 13% and 28% of overall biofuel production and delivery costs (dependent on the level of feedstock densification and the transport mode; Miao et al., 2011). Optimising the transportation stage is of great benefit to reducing overall biofuel production costs (Miao et al., 2011). Increasing feedstock yields has been shown to reduce transport costs by reducing the area of land required to supply feedstock (Nilsson, 2000); however, there is very little data on how much transport costs can be reduced when straw yield and digestibility is increased.

### 2.2.3. Environmental impacts from the supply of straw

Numerous studies have attempted to quantify the environmental impacts of lignocellulosic biofuel production. A key methodology used to quantify environmental impacts of SGB production is life cycle assessment (LCA). LCA is widely considered by the scientific community to be one of the best methods for the assessment of the environmental impacts of biofuels (Cherubini et al., 2009). There are a number of SGB LCAs and these studies have been extensively reviewed (e.g. von Blottnitz & Curran, 2007; Menichetti & Otto, 2009; Borrion et al., 2012a; Wiloso et al., 2012). The majority of studies compare environmental burdens of biofuel use to current road fuels, to determine whether environmental impacts can be reduced. Environmental burdens are highly variable but the majority of studies have found that GHG emissions from biofuels are lower than from fossil fuels but emissions of other pollutants, such as those causing eutrophication and acidification, tend to be higher for biofuels. Several studies have conducted LCAs for SGB from wheat straw in the UK (Borrion et al., 2012b; Wang et al., 2013). These have found that for the majority of environmental impacts, SGBs compare favourably with fossil fuels.

Although biofuels are seen as playing a role in reducing reliance on foreign fossil fuels and improving the rural economy, the major aspect of biofuels is the aim of reducing GHG emissions. However, environmental sustainability is not limited to climate change and other aspects of environmental sustainability must not be overlooked when assessing biofuels. This is important as other environmental burdens, such as natural resource depletion, could be increased whilst GHG emissions are being minimised and, therefore, information on all environmental burdens are needed to optimise trade-offs between different environmental impacts (Cherubini & Ulgiati, 2010).

### 2.3. Farmer willingness to supply straw and grow DPCs

Consideration of farmers' opinions is often neglected in biofuel policy even though they are key players in its viability; for example, Rossi & Hinrichs (2011) highlight US policy on feedstock supply, which they suggest is of 'macro-scale focus' whilst feedstock producers are seen as 'instruments' for the supply of feedstock, rather than as stakeholders. In reality, willingness to supply feedstock will vary greatly between farmers with some unwilling to sell straw (Tyndall et al., 2011). Glithero et al. (2013b), in surveying farmers in England, found a third would not supply wheat straw for bioenergy. Further work is required to determine potential feedstock supply for biofuel production, as well to assess whether farmers are willing to change their farming practices to increase straw yields.

### 2.4. Project aims

Given the above previous research into specific areas, this project had a number of aims:

- Explore variation in agronomic traits (straw and grain yield, lodging resistance and straw digestibility) in current cultivars under various management practices.
- Determine the gross margin value of straw to farmers and the potential increase in gross margins from using cultivars with higher straw yields and digestibilities.
- Determine the costs of collecting straw for a biorefinery and the impact on delivery charges from increasing overall straw yields and digestibilities.
- Quantify potential reductions in environmental burdens resulting from increasing straw yields and digestibilities using life cycle assessment (LCA).
- Determine current straw use and potential future supply using a postal survey.
- Provide recommendations to the stakeholders in the biofuel feedstock supply chain.

To investigate these, the project took a number of experimental approaches: 1) field trials to quantify key traits for multiple cultivars; 2) economic modelling to quantify the value of DPCs; 3) logistics modelling to quantify the costs of transporting straw from DPCs; 4) life cycle assessment to quantify environmental burdens of DPCs; and 5) a postal survey to determining farmer willingness to supply straw and grow DPCs.

## 3. Materials and methods

### 3.1. Cultivar trait measurements

A field experiment was conducted at the University of Nottingham's Farm at Sutton Bonington (52°50'N, 1°15'W) during the 2011–12 growing season. This field experiment followed on from the two field experiments conducted by Roy (2014). Three cultivars, Cordiale, Grafton and Xi19, which has been assessed in the field experiments conducted by Roy (2014) were selected based on current use (all three were in AHDB's 2011 Recommended List), high grain yields and differing characteristics in terms of height and lodging susceptibility.

The main objective of this experiment was to determine the influence of management practices on yield and digestibility. The field experiment investigated the effects of the PGR chlormequat and nitrogen (N) fertiliser application level on these traits. The N treatments were based on the N requirements of the field (based on RB209, 2010); all plots were given the first two splits of 40 kg $ha^{-1}$ and 80 kg $ha^{-1}$. The final split was 0 kg $ha^{-1}$ (N1), 50 kg $ha^{-1}$ (N2) or 100 kg $ha^{-1}$ (N3). The N2 treatment matched the recommended N application rate for the particular field, rotation and crop conditions.

The study comprised 18 combinations of cultivars and treatments, replicated three times in a block structure to account for fertility gradients in the field. A split-split plot design was used whereby each block was divided into three split plots (N treatment) that are each subdivided into two split-split plots (PGR treatments). This split-split-plot design was used to reduce PGR drift between treated and untreated plots, as well as the spread of N between the different treatments, which was further reduced by having discard plots (cv. Oakley) between the N treatment split-plots. Standard practices for fertilisers (other than N) and pesticides (other than PGRs) were used.

#### 3.1.1. Biomass assessments

Prior to harvest, all plants from within a 50 x 50 cm quadrat were collected. When plants were only partially in the quadrat they were only included if more than 50% of the plant was within the quadrat. These were dried in a glasshouse before being stored in a weatherproof crate. Ten plants were randomly selected and the roots were removed at ground level. For these plants, the main tiller was measured from the cut base to the top of the peduncle to give the straw length and the ear length was then measured to give total plant height.

The roots were removed from the remaining plants and these plants were added to the ten measured plants. This material was weighed and a 50% subsample was taken. The subsample was divided into stem, ears and leaf blades (leaf sheaf was included with stem). The stem was further divided into four parts:

S1 – the lower 10 cm from the stem base
S2 – the 5 cm section above S1 (10 cm to 15 cm from the stem base)
S3 – the 5 cm section above S2 (15 cm to 20 cm from the stem base)
S4 – the remaining stem (20+ cm from the stem base)

This material was placed into paper bags and oven dried at 80°C to constant weight. The ears were weighed before being threshed with a stand-alone thresher. The grain weight was then measured and the chaff weight calculated from the difference in weight between the ear and grain weight. Analyses were conducted for weights at 0% moisture content (MC), with weights converted to tonnes per hectare.

### 3.1.2. Lodging assessments

Lodging assessments were conducted using the lodging model described in Baker et al. (1998), which has been shown to be a good predictor of lodging susceptibility. Lodging assessments were conducted in 2011 and 2012 when the plants were at GS75. Samples were collected on June 28 in 2011 and July 17 in 2012. Approximately 12 plants were collected from each plot and kept in cold storage until the lodging assessments took place, which was no more than two weeks after being collected.

For the assessments, eight plants were selected from each plot and any odd features, such as heavy disease, were noted. The soil was gently shaken off the plants and the tillers were kept with the main stem. The root plate spread was measured between the furthest points of the structural roots. The plant was then rotated 90° and the furthest points of the structural roots were measured. The distance between the top of the roots to the end of the structural rooting depth was then measured.

Next, the numbers of shoots for each plant was counted before the main stem was separated from the tillers. The roots were then cut at the stem base and the height of the plant was measured from the base of the stem to the tip of the outstretched ear. The HCG was then measured by balancing the stem on a finger and then measuring the distance from the base of the stem to the point of balance. The natural frequency was measured by placing the very bottom of the stem in a vice, displacing the stem by 10 cm and timing how long it took for three oscillations. This was repeated three times to obtain the mean. The ear area was then measured using a leaf area meter.

The characteristics of internode 1 and internode 2 were measured. Internode 1 was taken as the first internode of longer than 10 mm, which had originated at or just below the ground surface (Berry et al., 2000). The length of each internode was measured from the centre of the node to the centre of the next node. The diameter at the centre of each internode was measured using digital callipers. The internode breaking strength was measured by balancing the internode on a Y-frame, attaching a spring balance hook around the centre of the internode and then pulling until stem failure and recoding the weight required for failure. Each internode was then cut in half and the stem wall width was measured at one point and then at 90° to that point.

For each plant the SFWS and RFWS were calculated using the calculations given in Baker et al. (1998). These eight failure wind speeds were averaged to give a SFWS and RFWS for each plot.

#### 3.1.3. Digestibility assessments

Assays were conducted to determine the influence of treatments on digestibility. This work was conducted by a third party at the University of Nottingham following the methodology described in Roy (2014). The work first determined the total amounts of glucose present in the material and then the amount of sugar released under specific pretreatment conditions. These pretreatments were optimised to show differences between cultivars rather than to maximise glucose release so glucose yields are lower than those expected for biofuel production. Known samples from cv. Orbit were used as a control.

Three comparisons were conducted: 1) a comparison of four stem and leaf components of Xi19 for PGR and N treatments; 2) a comparison of stem and leaf of Cordiale and Grafton for PGR treatments; and 3) a comparison of whole plants of Xi19, Cordiale and Grafton for PGR treatments.

#### 3.1.4. Statistical analysis

The statistical package GenStat ($16^{th}$ edition; VSN International Ltd.) was used to analyse the data. The data was checked to see if it met the assumptions of general linear models. ANOVA was used in the comparison of the treatments with the Bonferroni post-hoc text used to determine which groups significantly differed. To take account of the split-split plot design, “Block/Nitrogen/PGR” was used as the blocking design for the ANOVA, except where noted in the text.

## 3.2. Economics

The economics work examined the potential value of straw to farmers and the potential value of dual-purpose cultivars. Gross margins (GMs) were calculated for straw and overall gross margins for nine hypothetical cultivars. The gross margins took into account the amount of nutrients removed from the soil in the straw based on the average straw nutrient content (**Table 1**). The value of the fertiliser required to replace these nutrients was calculated using the prices from (ABC, 2013; **Table 2**). The calculations assumed that the farm does not have baling equipment and this operation is conducted by a contractor. Contractors' fees were based on average values presented in NAAC (2012). The model calculates the overall cultivar GM for the hypothetical cultivars for multiple straw values based on the price of grain and straw, less the variable costs for its production (**Eq. 1, 2**).

$$GM_s = \left(SY \times \left(S_p + P_d\right)\right) - VC \qquad \textbf{Eq. 1}$$

$$VC = \left(SY \times (F \times FP)\right) + CC \qquad \textbf{Eq. 2}$$

Where: $GM_s$ = straw gross margin; $SY$ = straw yield (t ha$^{-1}$); $S_p$ = straw price (£ t$^{-1}$); $P_d$ = straw digestibility premium (£ t$^{-1}$); $VC$ = variable costs (£ ha$^{-1}$); $F$ = amount of fertiliser (kg t$^{-1}$ straw); $FP$ = price of fertiliser (£ t$^{-1}$); $CC$ = contractor charges (£ ha$^{-1}$).

***Table 1:*** *Fertiliser requirements per tonne straw (fresh weight).*

| Nutrient | Mean (kg) | Source |
|---|---|---|
| $K_2O$ | 9.5 | RB209 (2010) |
| $P_2O_5$ | 1.2 | RB209 (2010) |
| N | 6.2 | Alberta Agriculture (2009, as cited by Levelton Engineering Ltd., 2000); Wortmann et al.(2008); IPNI (2008); MAFRD (2014) |
| MgO | 1.3 | AHDB Cereals & Oilseeds (2009) |
| $SO_3$ | 3.7 | Wortmann et al. (2008); IPNI (2008); MAFRD (2014) |

***Table 2:*** *Average fertiliser prices delivered (from ABC, 2013).*

| Fertiliser | Price (£ t$^{-1}$) |
|---|---|
| $K_2O$ | 508.5 |
| $P_2O_5$ | 663 |
| N | 813 |
| MgO | 1096 |
| $SO_3$ | 420.5 |

### 3.2.1. Hypothetical cultivars

As the range of straw yields and digestibility were relatively small from the crop experimental cultivars, hypothetical cultivars with a larger range of trait values were used in the economic analysis, as well as in the logistics analysis and LCA, to assess the impact of potential ranges in yields and digestibilities.

Nine hypothetical cultivars were assessed. For these cultivars, the grain yield and quality was assumed to be equal. The straw yields used were 4, 5 and 6 t $ha^{-1}$ and these values represent the amount of straw baled and available to be sold. The lower value represents a just above average straw yield (3.5 t $ha^{-1}$; Nix, 2013), the middle value represents the estimated yield in the land supplying Ely (Anon, 2012) and the upper value represents a cultivar managed for higher straw yield. A value of 16% MC was used based on the average value at Ely (Newman, 2003) and it was assumed that the MC is 16% at the farm gate and the biorefinery gate.

Three straw digestibility levels were modelled (represented as D1, D2 and D3). Wheat cultivars have been found to vary in digestibility (e.g. Lindedam et al., 2010; Jensen et al., 2011; Lindedam et al., 2012); however, the extent of variability differs between studies. Jensen et al. (2011) found a 37% range whilst Lindedam et al. (2010) found a 15% range; however, it is unclear what the extent of digestibility differences between cultivars will be under industrial-scale production. Some studies have not found a significant difference between cultivars (Larsen et al., 2012). There are also questions about how fixed digestibility for each cultivar with digestibility variation between sites and experimental years in the literature. For this reason the values used in the current assessment were conservative compared to Jensen et al. (2011) and Lindedam et al. (2010) and represent a smaller range of digestibility. The baseline digestibility (D1) for this study was taken as 335 L $odt^{-1}$ straw (based on Borrion et al., 2012). The intermediate value (D2) was 2.5% higher than D1 (343 L $odt^{-1}$ straw) and the most digestible material (D3) represents a wheat plant with an ethanol yield 5% higher than the baseline (352 L $odt^{-1}$ straw). The amounts of straw at 0% MC required to produce 1 litre of bioethanol were: 2.54 kg $L^{-1}$ (D1), 2.48 kg $L^{-1}$ (D2), and 2.42 kg $L^{-1}$ (D3).

### 3.2.2. Gross margins and variable costs

The model calculated GMs for the cultivars from output values and variable costs. To simplify the study and analysis, the model uses average values from sources used by farmers when making budgeting decisions. Variable costs were taken from the Agricultural Budgeting and Costing Book (ABC, 2013) and The John Nix Farm Management Pocketbook (Nix, 2013). Both Nix and ABC use average values across the UK but the actual variable costs incurred by farmers can differ greatly from the average values. The model, therefore, does not necessarily reflect the true values farmers will achieve but does provide a comparison of price differences between cultivars.

It is unclear how much would be offered for straw for biofuel production. The model considered multiple values of straw to assess the relationship between grain and straw yield. GMs were calculated for a minimum value of £40 $t^{-1}$ and a maximum value of £100 $t^{-1}$. For the main analysis, the straw price is taken as £47.38 $t^{-1}$ (average price for straw in England and Wales, big square bale, January 2010 to January 2014; Defra, 2014). Straw is assumed to have 16% MC.

The model considers a value premium based on digestibility of the straw. The prices are assumed to be the same as the percentage increase in digestibility, in this case a rise of 2.5% and 5% of the straw price (or 2.1% and 4.2% when considered for straw at 16% MC). For a price of £47.38 $t^{-1}$ straw, the price for D2 and D3 digestibility is £48.37 and £49.37 $t^{-1}$, respectively.

### 3.3. Logistics

The costs of transporting straw from the hypothetical cultivars described above are quantified using a *type 1 simple continuous* transport model based on examples by Overend (1982), Huang et al. (2009) and Leboreiro & Hilaly (2011). The model assumes a feedstock demand of 500,000 tonnes $yr^{-1}$ which gives an annual ethanol production capacity of 196.9 ML. As material of higher digestibility produces a greater ethanol output, less straw is required to produce the same ethanol output. Feedstock demand is expressed as dried weight (i.e. 0% MC) whilst straw is received with 16% MC. The model calculates transport costs for delivery of 1 tonne of straw as well as the equivalent straw required to produce 1000 L bioethanol for each hypothetical cultivar.

The first part of the model calculates the geographic area required to supply the required amount of straw. The model assumes that straw is collected from a circular area with the biorefinery at the centre of the circle and straw supply evenly distributed throughout (**Eq. 3**).

$$R = \left(\frac{F}{\pi S Y}\right)^{0.5} \quad \textbf{Eq. 3}$$

Where: *R* = radius of circle required to source feedstock; *F* = annual feedstock demand; *S* = fraction of farmland supplying feedstock, which is determined by the proportion of land producing wheat and the proportion of straw from this wheat area that farmers are willing to supply. *Y* = biomass yields at 16% MC.

The area of land supplying straw (*S*) is estimated using the values given for the planned and current bioenergy facilities in the UK. The Ely plant uses 200,000 tonnes collected, on average, within a 48 km radius (Anon, 2012a) and the Sleaford power plant, currently under construction, is expected to use 240,000 tonnes, almost all of which is expected to be collected from within a 48 km radius (Eco2 UK, 2014). Assuming an average yield of 5 t $ha^{-1}$ suggests that approximately 7% of land within the 48 km radius is supplying straw to the plant.

The average haul distance is calculated using **Eq. 4** based on Overend (1982) but including both the outward and return journeys because the truck will be travelling empty to the farm. It is possible that ash from the biorefinery could be returned to the fields as fertiliser and this could be delivered in the outward journey; including a haul in the outward journey would reduce the cost attributed to transporting biomass (Kaylen et al., 2000). This has not been considered in the current model.

$$D = \frac{4}{3} R \times \tau \quad \textbf{Eq. 4}$$

Where: *R* = radius of total supply; *D* = average haulage distance; $\tau$ = tortuosity factor

The tortuosity factor ($\tau$) is the ratio of actual distance travelled to straight-line distance, the use of which has been shown to be an accurate method for predicting actual distances from straight line distances (Boscoe et al., 2012). In the current study a value of 1.5 is used for $\tau$. It is assumed that $\tau$ does not change as the average straight line distance increases.

The feedstock delivery price consists of distance-fixed costs and distance-variable costs (Huang et al., 2011). Cost calculations are based partly on Anon (2003). It is assumed that a 44-tonne gross (6x2 + tri-axle) combination truck with a trailer is used. The costs for these are taken from the Road Haulage Association costs tables prepared by DFF International LTD (DFF, 2013), which are based on average haulage costs in the UK. The costs per day, inclusive of drivers' wages, are £346 for the truck and £11 for the trailer; assuming an 11 hour day (Anon, 2003) this gives costs of £32.45 $hr^{-1}$. Distance-variable costs consist of the travelling time costs, which are calculated using the distances generated by the model, assuming an average speed of 56 km $h^{-1}$ (Anon, 2003), and an additional cost of 52.27p $km^{-1}$ for fuel, etc. Distance-fixed costs are calculated as the loading at the farm and the unloading at the biorefinery; this consists of the cost of carrying out these operations as well as the costs associated with the truck waiting for these operations to be completed. Loading cost is taken as £35 $hr^{-1}$ (forklift/telehandler plus operator; NAAC, 2012) and loading time is 46 minutes (1 minute per bale and 10 minutes to cover the load; Rogers & Brammer, 2009). The unloading at the biorefinery is assumed to be carried out by automatic gantry crane as with Ely Power Station (e.g. Newman, 2003). Therefore, the only costs included are the time costs of the truck waiting (assumed to be 30 minutes) while this process is completed (Rogers & Brammer, 2009).

### 3.4. Environmental impacts

A partial (cradle-to-gate) LCA, starting with the production of wheat and finishing with delivery at the biorefinery gate, was conducted to quantify the environmental burdens (EBs) from producing wheat straw for biofuel production from DPCs. The conversion process is not included in this study but published data on the conversion process (Borrion et al., 2012b) is used as a reference system. The product being assessed is the wheat straw feedstock required to produce cellulosic ethanol, delivered to the biorefinery gate. The LCA covers the cultivation of wheat, the baling of straw, on-farm transport and the transport from the farm gate to the biorefinery. The wheat production system is based on standard best practice in England using average values for inputs and farm processes. The LCA was conducted using SimaPro LCA software (version 8.0.2) and the EcoInvent database (version 3.0).

Allocation is the process whereby the EBs are shared amongst multiple products**.** Multiple allocation scenarios are used to determine the share of emissions between the grain and straw from the wheat production subsystem: **A1)** Straw is treated as a by-product and all inputs for the production of grain are allocated to the grain. **A2a)** Straw is treated as a co-product and all processes including straw baling, carting and unloading, and grain transport are combined. Environmental burdens are allocated between the grain and straw based on economic value. From the economic model, grain value is £152.5 $t^{-1}$ and straw value is £47.38, £48.56 and £49.75, for D1, D2 and D3, respectively. **A2b)** As with A2a but instead of economic values, the EBs are shared between grain and straw based on the gross margins. **A2c)** Straw is treated as a co-product and all processes including straw baling, carting and unloading, and grain drying and transport are combined. Environmental burdens are allocated between the grain and straw based on the mass of grain and straw.

Due to two main allocation methods being utilised, two product flow charts are provided (**Fig. 1a, b**). The first model represents the A1 allocation method whilst the second model represents the A2a-c allocation methods.

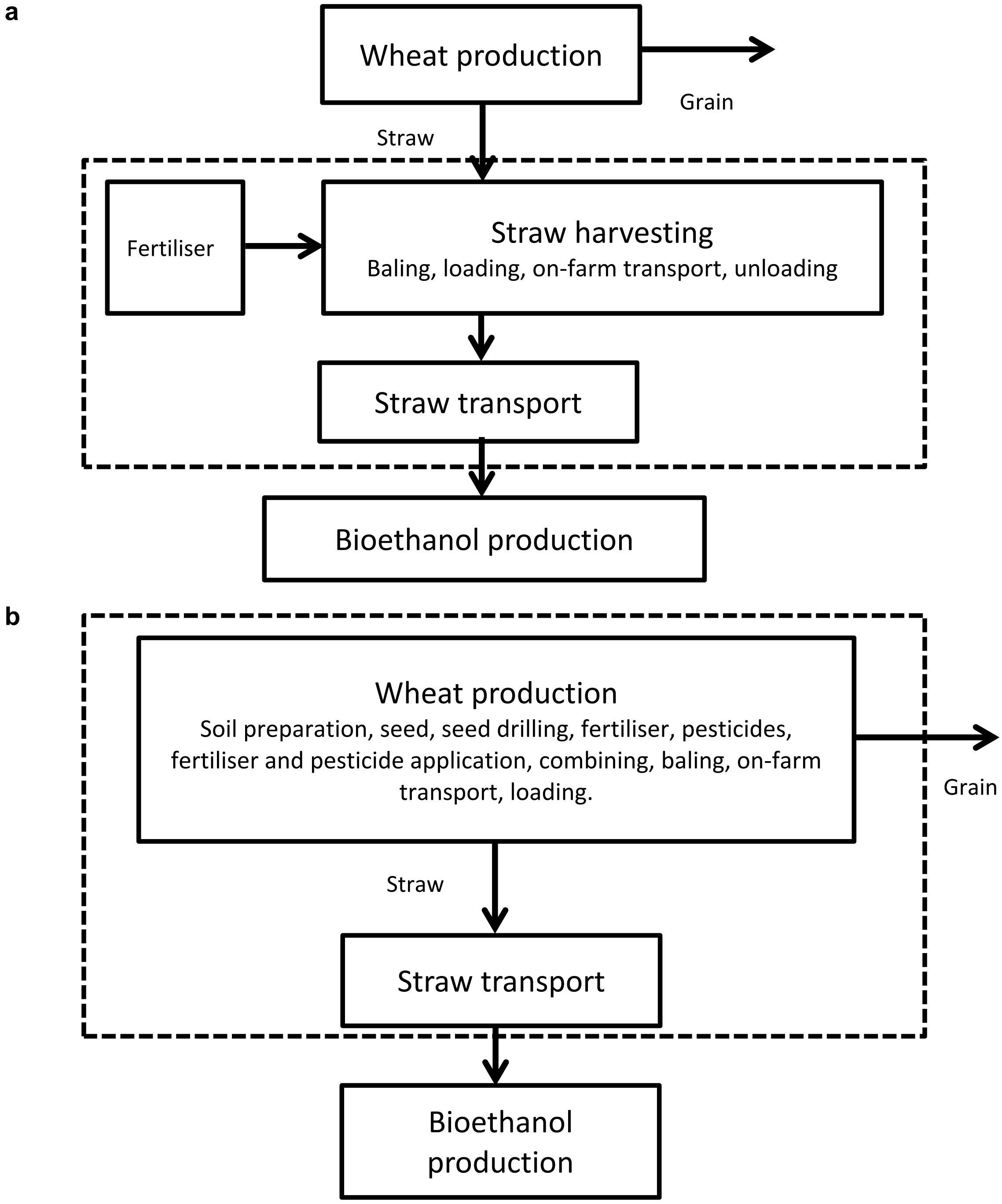


***Figure 1a, b:*** *Product flow chart demonstrating allocation system A1 (**a**) and allocation system A2a-c (**b**). Dashed lined represents the system boundaries.*

### 3.5. Survey

To explore current straw uses and future straw supply a postal survey was conducted winter 2012. 2,000 questionnaires were sent to farms in counties in eastern England as these are the counties with the greatest straw availability (Copeland & Turley, 2008). The addresses were selected from phone directories. The questionnaire asked for information about the location of the farms and the types of crops and livestock kept. The survey asked about the characteristics that the farmers base their wheat cultivar choice on and the sources of information they use to select cultivars. The respondents were asked about their wheat straw use from the 2012 harvest. They were asked whether they would be willing to increase straw supply by increasing straw yields, the price they would do this for, and the management practices would they use to achieve this.

Pearson chi-square was used to test the hypothesis that there is no association between group descriptors (e.g. farm size groups) and stated actions or attributes. After a significant test, post hoc pairwise comparison of groups with aggregation of non-significantly different groups was used to determine which groups differed. Some data was grouped to avoid expected values lower than five. In particular, Likert-scale ratings for *Very unimportant* and *Unimportant* were aggregated with *Neutral*, as these were only very rarely selected. For straw price comparisons, ANOVA was used to compare the groups. Two values (£500 and £1,000) were excluded from the analysis as these skewed the results. However, it is accepted that some respondents would require much higher prices before they start to manage for increased straw yield. For the straw use analysis, the proportion of straw that was chopped and incorporated was analysed. Firstly, ordinal regression was used to compare groups based on the number of respondents chopping and incorporating all of their straw. This was then followed by ordinal regression (with multinomial distribution and logit link function) to compare groups based on the number of respondents chopping and incorporating none of the straw. Then general linear regression was used to compare groups based on the proportion of straw chopped and incorporated excluding farms where all or none of straw was chopped and incorporated.

# 4. Results

## 4.1. Cultivar trials

### 4.1.1. Biomass assessments

Grain yields were significantly influenced by cultivar (**Fig. 2**). Xi19 was significantly lower than Cordiale and Grafton for both quadrat ($P$ <0.001) and combine ($P$ <0.001). Grain yield increased with PGR application ($P$ = 0.040).

The four stem sections differed in how they responded to the treatments (**Fig. 3**). For the first section (S1) PGR application increased yield ($P$ = 0.036), N had an influence with N2 being significantly greater than N1 with N3 an intermediate value ($P$ = 0.036) whilst Xi19 had significantly lower stem biomass than the other cultivars ($P$ = 0.011). The fourth section (S4) was influenced by cultivar ($P$ = 0.001), with Xi19 having significantly more biomass than Grafton, and PGR lowered straw yield ($P$ = 0.009). The middle sections (S2 and S3) did not significantly vary with treatment and there were no significant interactions. When the total stem was considered there were no significant differences between treatments.

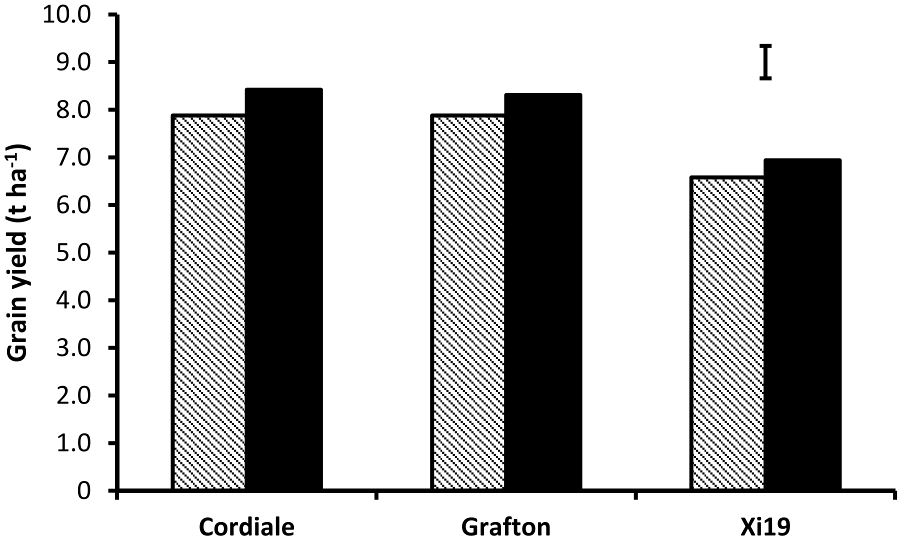


***Figure 2.*** *Grain yields for the three cultivars and PGR treatments. PGR: untreated (diagonally-lined bars); treated (solid bars). Error bars show S.E.D for the cultivar-PGR interaction.*

The data allows an assessment of the influence that combine header height might have on straw yields. At a header height of 10 cm (S2-S4; 'upper stem') there was a significant cultivar effect ($P$ = 0.036) with Xi19 having significantly more biomass than Grafton, with Cordiale having an intermediate yield, matching height order. Increasing the header height to 15 cm (S3+S4) led to PGR application significantly lowering straw yield ($P$ = 0.036) whilst the significance of cultivar increased ($P$ = 0.007). At a header height of 20 cm (S4) the significance level of cultivar ($P$ = 0.001) and PGR ($P$ = 0.009) increased. However, even with this increased significance, Cordiale did not become significantly different from the other cultivars.

Cultivar significance was only found for the upper stem and not for the whole stem. This was because the lower 10 cm of stem for Xi19 had a significantly lower yield than Cordiale and Grafton, negating the higher yield it has for the remaining stem. This suggests that if the straw were to be baled, Xi19 would have a significantly higher yield than the other cultivars even though the overall straw production was even. On average, increasing simulated cutter height from 10 cm to 15 cm reduces straw yield from 4.70 t $ha^{-1}$ to 4.12 t $ha^{-1}$, a 12.4% decrease. Increasing simulated cutter height from 15 cm to 20 cm, decreases straw yield to 3.58 t $ha^{-1}$, which is a further decrease of 13.2%. These decreases in straw yield are more pronounced for the PGR-treated yields than non-PGR-treated yields. They are also greater for Grafton than Cordiale, which in turn is greater than Xi19.

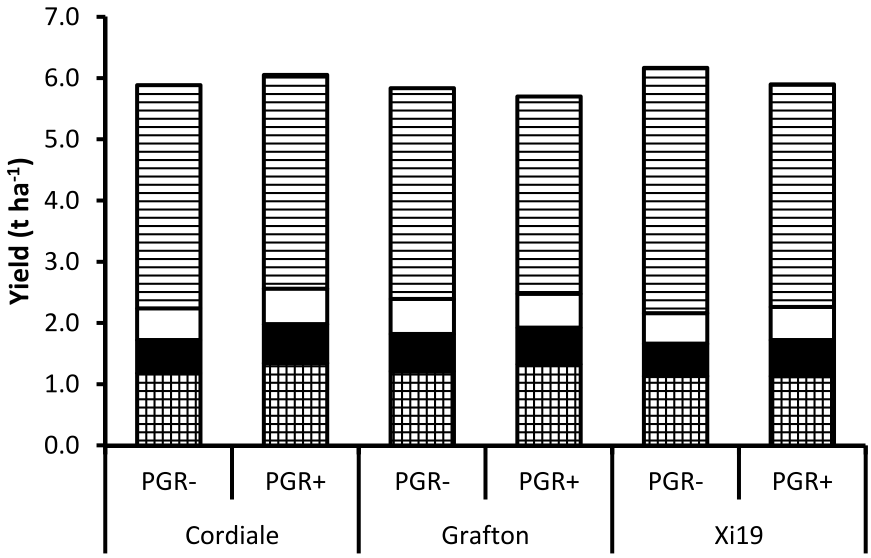


***Figure 3**. Header height and straw yields. S1 (checked bars); S2 (white bars); S3 (solid bars); S4 (horizontally-lined bars). SEDs for the cultivar-PGR interaction are 0.064 (S1), 0.047 (S2), 0.038 (S3) and 0.147 (S4).*

When total stem and leaves are combined (total stem plus leaf), no treatments had a significant influence. Leaf yield was significantly lower for N3 than N2, with N1 having an intermediate value (*P* = 0.034) and Grafton had significantly more leaf than the other cultivars (*P* <0.001). PGR did not have a significant influence. Leaf-to-stem ratio was significantly different between all three cultivars (*P* <0.001), with Xi19 lowest, followed by Cordiale and then Grafton. This is a result of Xi19 having highest stem but lowest leaf mass and Grafton having the highest leaf mass but lowest stem mass. Chlormequat application did not significantly influence the ratio but N did with N1 being significantly higher than N3, with N2 having an intermediate value (*P* = 0.040).

Xi19 had significantly lower total biomass than Cordiale and Grafton (*P* = 0.017; **Fig. 4a**). The application of PGRs led to a non-significant increase in total biomass for all cultivars. Xi19 also had a significantly lower HI than Grafton and Cordiale (*P* <0.001; **Fig. 4b**) due to it having a lower grain yield than the other cultivars but a similar straw yield. There was a general, non-significant (*P* = 0.090) pattern of PGRs increasing HI due to the slight increase in quadrat-sampled grain yield and slight reduction in straw yield seen with the application of PGRs. To consider the straw to grain relationship, the upper stem mass was divided by the quadrat grain yield to get a straw-to-grain ratio. Xi19 had a significantly higher ratio than Cordiale and Grafton (*P* <0.001) and PGRs significantly increased this ratio (*P* = 0.005).

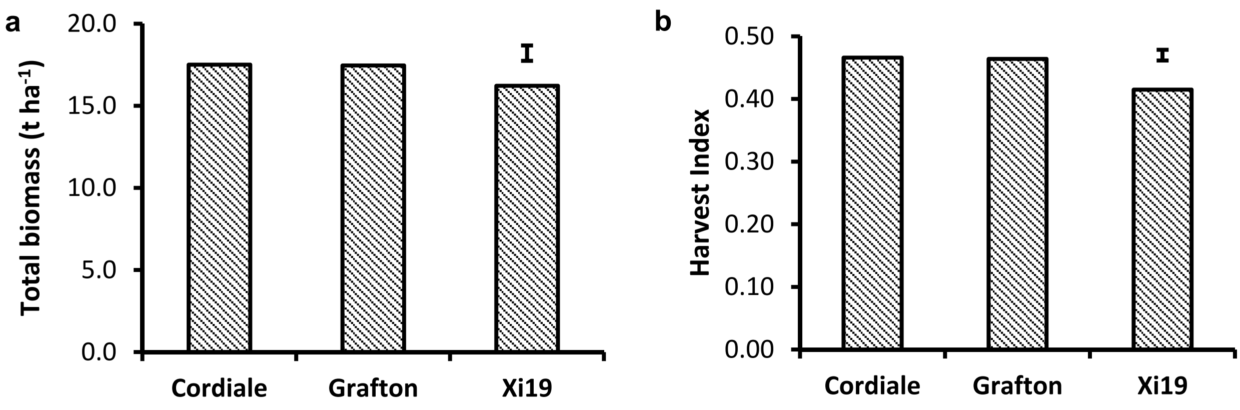


***Figure 4a, b**. Total biomass for cultivars (**a**); harvest indices for cultivars (**b**). Error bars show SED for the cultivar-PGR interaction.*

### 4.1.2. Lodging assessments

Only very minor lodging was present in the field experiment. Small areas of plots 40 (Xi19 N2, no PGR) and 42 (Cordiale N2, no PGR) suffered from stem lodging where the stems were displaced approximately 45 degrees. SFWS was lower than RFWS for all plots indicating that the plants were more likely to stem lodge than root lodge. Xi19 had a significantly lower SFWS than Cordiale and Grafton (*P* <0.001). PGRs increased the SFWS (*P* = 0.001; **Fig. 5**) whilst N had no effect. There was no significant interaction between cultivar and PGR application; however, PGR applications increased SFWS on average by 0.69, 1.35 and 1.78 m $s^{-1}$ for Xi19, Grafton and Cordiale, respectively. RFWS was significantly influenced by cultivar, with Grafton having a higher RFWS than Cordiale and Xi19 (*P* <0.001), but not by N or PGR. PGR application caused a general non-significant trend in increasing RFWS.

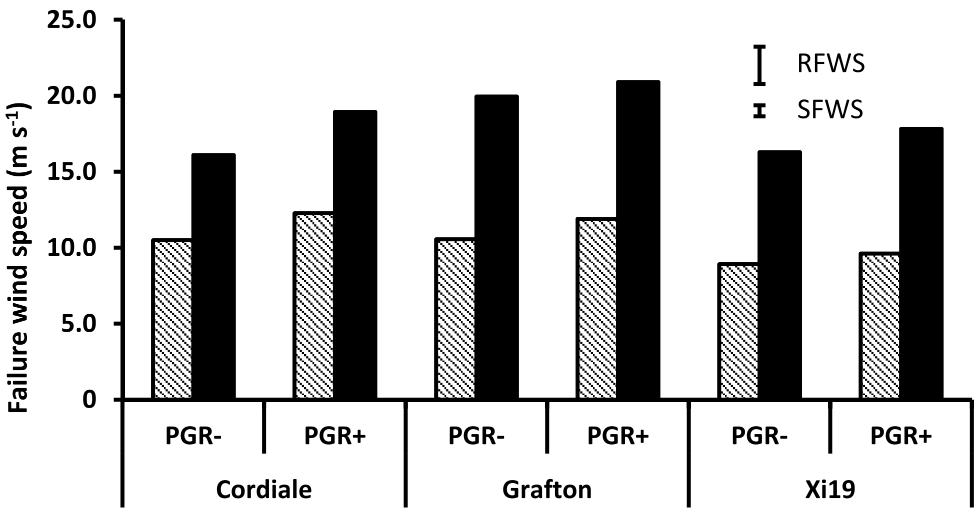


***Figure 5**. Stem and root failure wind speeds for cultivars and PGR treatments. Failure wind speed: SFWS (diagonally-lined bars); RFWS (solid bars). Error bars show SED for the cultivar-PGR interaction with label referring to the corresponding data.*

SFWS is determined by the stem leverage and material strength. For all but two plots (Xi19 N3, PGR-, Cordiale N2, PGR-) the SFWS was lowest for internode 2, indicating that the point of stem failure would occur in internode 2. However, the characteristics of both internodes are considered below to see whether the treatments influence them. Stem leverages of both internodes were significantly lower for Xi19 than the other cultivars (*P* <0.001 for both) and lower with the application of chlormequat (*P* = 0.001 and *P* <0.001, respectively); and N1 was significantly lower than the other N levels (*P* = 0.041 and *P* = 0.035, respectively). The material strength of internode 1 was significantly higher for Cordiale than the other cultivars (*P* <0.001) but was not influenced by PGR or N. There was a significant interaction between N, PGR and cultivar (*P* = 0.024) resulting from Cordiale varying considerably more than the other cultivars between PGR treatments for different N levels. For internode 2, Grafton was significantly lower than Xi19, which in turn was significantly lower than Cordiale (*P* <0.001). Neither PGR nor N had an influence. From this it can be seen that SFWS was lowest for Xi19 due to it having high stem leverage and an intermediate stem material strength.

RFWS depends on anchorage strength as well as stem leverage on the root system, which is leverage on internode 1 multiplied by the number of shoots. Anchorage strength was significantly lower for Cordiale than the other cultivars (*P* <0.001) but PGR (*P* = 0.942) and N (*P* = 0.679) did not have a significant influence. Leverage strength was significantly higher for Xi19 (*P* <0.001) and without chlormequat (*P* = 0.002).

### 4.1.3. Digestibility assessments

The lower and upper stem components were significantly less digestible than the peduncle, which in turn was significantly less digestible than leaf (*P* <0.001; blocking structure: block/nitrogen/plant). PGR application increased digestibility (*P* = 0.049; **Fig. 6**), but N did not have a significant influence. Although there was not a significant difference between the N treatments, there was an overall pattern of decreasing digestibility with increasing N application.

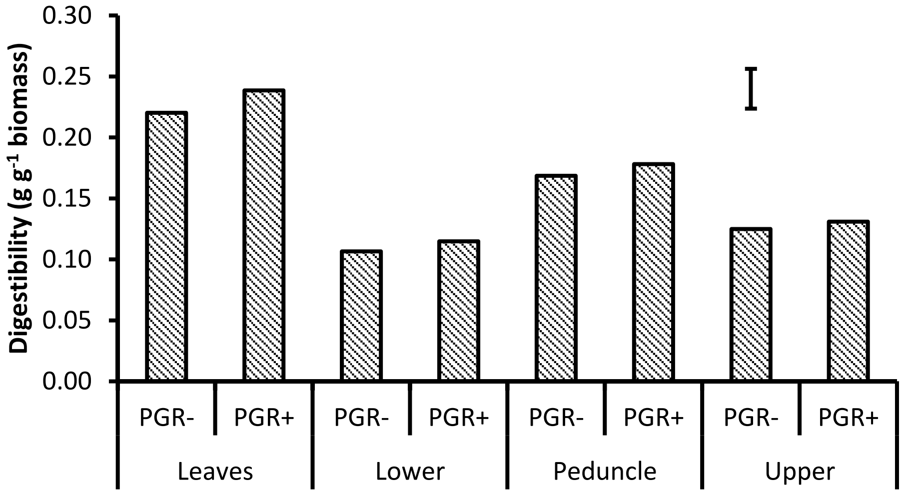


***Figure 6****. Digestibility means for fractions of Xi19 and PGR treatments. Error bar shows SED for the fraction-PGR interaction.*

Leaf had significantly less glucose than the other components (*P* <0.001). The lower glucose content in leaves is in contrast to their higher digestibility. There was a non-significant trend with glucose content decreasing with increasing N applied (*P* = 0.097). PGR was not significant. When the two fractions of Cordiale and Grafton were analysed, leaf was significantly more digestible than stem (*P* <0.001; blocking structure: block/PGR/plant) and PGR application significantly increased digestibility (*P* = 0.023; **Fig. 7**), but cultivars did not significantly differ.

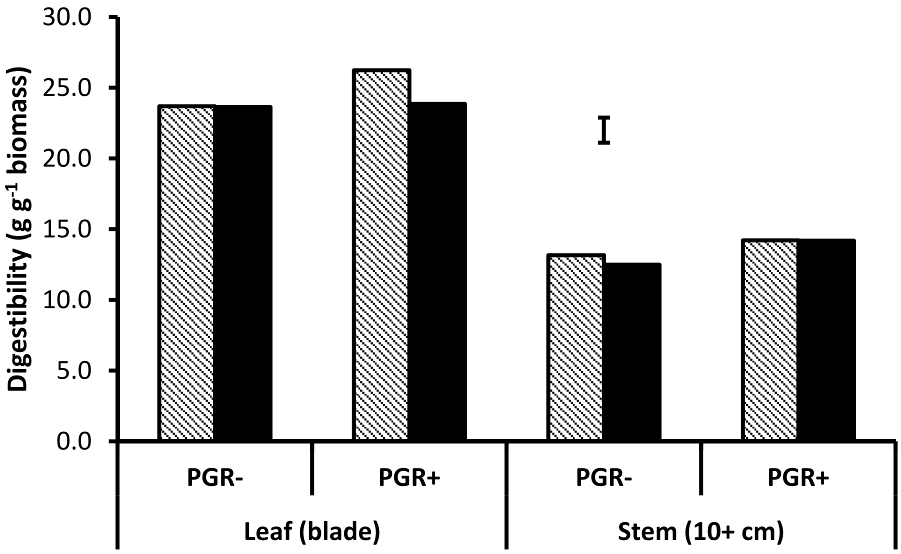


***Figure 7.*** *The effect of PGR, cultivar and plant fraction on digestibility. Cultivars: Cordiale (solid bars); Grafton (diagonally-lined bars). Error bar shows SED for the cultivar-PGR-fraction interaction.*

There were strong non-significant trends for higher sugar for stem compared to leaf and for the application of chlormequat. For the total sugars present there were significant interactions between

PGR and fraction (*P* = 0.032), and between the three treatments (*P* = 0.032); the interaction between PGR and cultivar was almost significant (*P* = 0.056). The interactions appear to result from there being such a large difference between the stem fraction of Cordiale with and without PGR; the mean for the plots without chlormequat application was 26.72% and was 41.42% for those treated with chlormequat; this difference is substantial when compared to the results for all the other treatments which ranged from 31.79% to 36.91%. It is unclear why this has occurred and it does not appear to be reflected in the digestibility results.

The digestibility of whole plant samples was compared between the three cultivars and PGR treatments. Grafton had a significantly greater digestibility than Cordiale, with Xi19 having an intermediate digestibility (*P* = 0.017; **Fig. 8**; blocking structure: block/PGR) but PGRs did not have a significant impact. The reason why the effect of PGR was significant when Xi19 was analysed independently is because the N1 and N3 treatments gave a much larger difference between PGRs treatments than N2. Excluding N1 and N3 from the analysis meant that this significance is harder to find. The mean values follow the general trend of PGRs increasing digestibility.

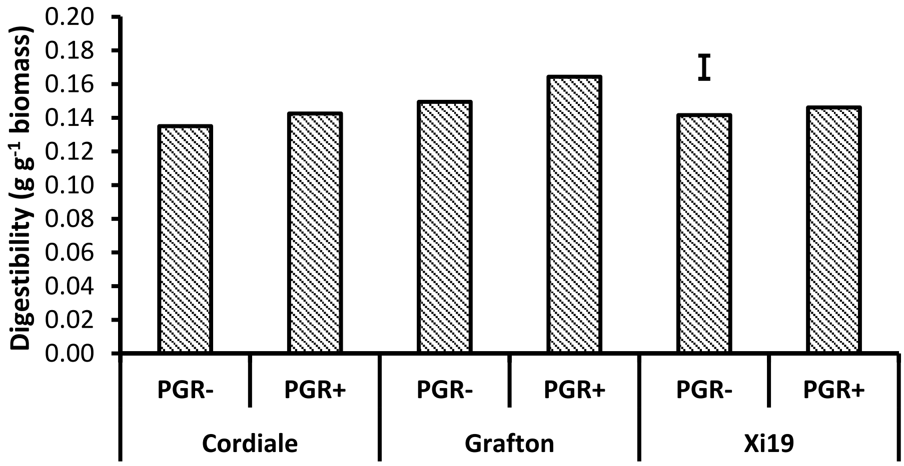


***Figure 8.*** *Digestibility means for the whole plant samples for the three cultivars. Error bar shows SED for the cultivar-PGR interaction.*

Xi19 had approximately 50% more total mass that was glucose than Cordiale and Grafton (P <0.001). The reason for this is unclear; however, it does not appear to have influenced digestibility. PGRs did have a significant impact (*P* = 0.011) with much smaller sugar yields for Grafton and Cordiale without PGRs applied. Xi19 glucose content was the same for both PGR treatments.

### 4.2. Economics

The fertiliser costs per tonne of straw were £13.65 and the baling charges were £17.74, giving overall variable costs of £31.38 $t^{-1}$ (**Fig. 9**). The baling stage contributed the largest part of the variable costs. N and K fertilisers had the next biggest contributions, demonstrating their importance to overall price.

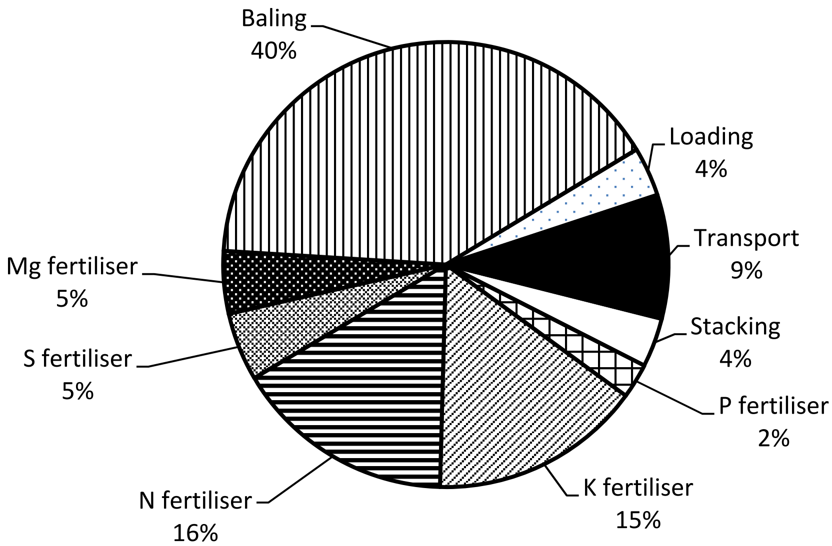


***Figure 9.*** *Percentage breakdown of the costs for baling, on-farm transport and replacement nutrients for 1 tonne of straw.*

For a straw price of £47.38 $t^{-1}$, gross margins are £16.00 $t^{-1}$. For the higher digestibility straw, the gross margin is £17.18 $t^{-1}$ and £18.36 $t^{-1}$, for D2 and D3 straw, respectively (**Table 3**). When the chopping credit is taken into account (assuming a 5 t $ha^{-1}$ straw yield), these values are £17.10 $t^{-1}$, £18.28 $t^{-1}$ and £19.47 $t^{-1}$, for D1, D2 and D3, respectively.

***Table 3.*** *Gross margins (GM) for straw and grain for the nine hypothetical cultivars and their contributions to the overall gross margins.*

| Cultivar | Straw GM (£) | | Grain GM (£) | | Total GM (£ $ha^{-1}$) | GM % Contribution | |
|---|---|---|---|---|---|---|---|
| | $t^{-1}$ | $ha^{-1}$ | $t^{-1}$ | $ha^{-1}$ | | Straw | Grain |
| 4D1 | 16.00 | 63.98 | 95.13 | 761 | 824.98 | 7.8% | 92.2% |
| 5D1 | 16.00 | 79.98 | 95.13 | 761 | 840.98 | 9.5% | 90.5% |
| 6D1 | 16.00 | 95.97 | 95.13 | 761 | 856.97 | 11.2% | 88.8% |
| 4D2 | 16.99 | 67.96 | 95.13 | 761 | 828.96 | 8.2% | 91.8% |
| 5D2 | 16.99 | 84.95 | 95.13 | 761 | 845.95 | 10.0% | 90.0% |
| 6D2 | 16.99 | 101.94 | 95.13 | 761 | 862.94 | 11.8% | 88.2% |
| 4D3 | 17.99 | 71.94 | 95.13 | 761 | 832.94 | 8.6% | 91.4% |
| 5D3 | 17.99 | 89.93 | 95.13 | 761 | 850.93 | 10.6% | 89.4% |
| 6D3 | 17.99 | 107.91 | 95.13 | 761 | 868.91 | 12.4% | 87.6% |

Of the farms surveyed as part of this project the average area of wheat in East Midlands and the East of England was 216 ha. Assuming that a third of the straw is sold, at 5 t ha$^{-1}$ straw yield and a price of £47.38 t$^{-1}$, this could result in an annual average farm GM from selling straw of £5,760.00 (£6,157.44 including the chopper credit). For the nine hypothetical cultivars, the potential gross margins ranged from £4,608.00 to £7,931.52 (£5,005.44 to £8,328.96, including the chopper credit; **Fig. 10**).

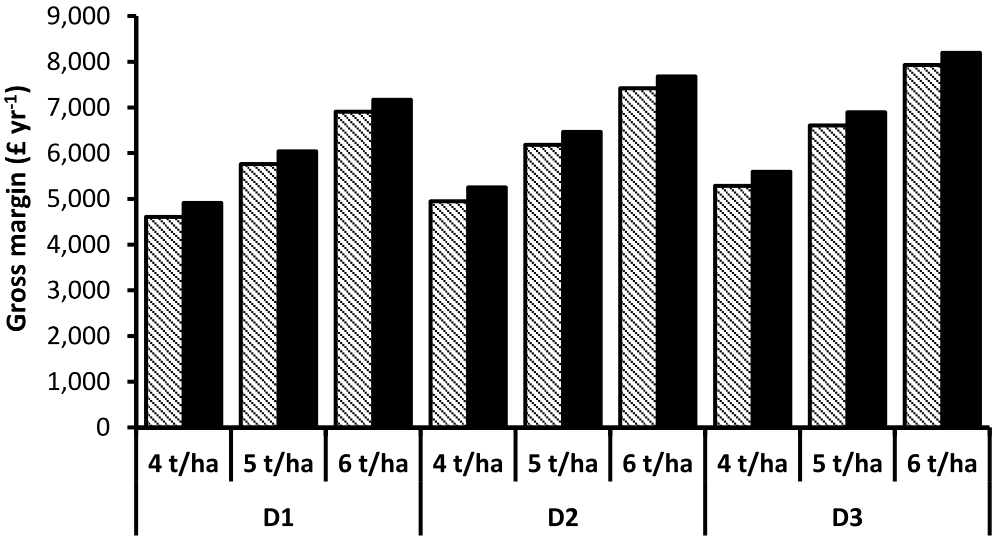


***Figure 10.*** *Annual gross margin of nine hypothetical cultivars on a farm supplying 72 ha yr$^{-1}$ of straw. Chopper: no chopper credit (diagonally-lined bars); with chopper credit (solid bars).*

Based on the fertiliser prices, this suggests a minimum price for selling straw in the swath for 4 t ha$^{-1}$ straw yield is £54.59 ha$^{-1}$ (£49.07 including chopper credit). The ABC (2013) gives an average value for straw in the swath of £60 ha$^{-1}$, which gives a gross margin of £6.41 ha$^{-1}$. With the same farm as above this would equal an annual straw gross margin of £461.52 per farm. For a straw price of £47.38 t$^{-1}$, the GMs of the straw contribute between 7.8% and 12.4% of the overall crop GMs (**Table 3**). The straw variable costs are approximately 66% of the straw price whereas for grain this is approximately 37% of price. This suggests that determining the value of grain and straw to farmers cannot be based on prices alone.

When selling straw in the swath, the straw yield must be taken into account. If the straw yield is at 1.5 t ha$^{-1}$, the GM is £39.52 ha$^{-1}$, which is greater than the straw GM (£24 ha$^{-1}$) for selling the straw baled at £47.38 t$^{-1}$. Selling straw in the swath for £60 ha$^{-1}$ for straw yields above 4.4 t ha$^{-1}$ would lead to an economic loss as the value of the nutrients being removed from the field exceeds £60 ha$^{-1}$.

### 4.3. Logistics

Increasing straw yield from 4 t ha$^{-1}$ to 5 t ha$^{-1}$ and 6 t ha$^{-1}$ reduced biomass feedstock delivery distance by 10.56% and 18.35%, respectively. For a 500,000 t yr$^{-1}$ feedstock demand, this is equal to a round-trip distance reduction of 17.37 km and 30.19 km for 5 t ha$^{-1}$ and 6 t ha$^{-1}$, respectively. Increasing digestibility has very little impact on transport distances with only 1.23% and 2.41% decreases in transport distances for increasing digestibility from D1 to D2 and D1 to D3, respectively; for 5 t ha$^{-1}$ yields supplying a 500,000 t yr$^{-1}$ biorefinery this reduction is equal to 1.81 km and 3.55 km decreases in round-trip distance, respectively (**Fig. 11**). When digestibility and yield are considered together, there is a reduction of 20.32% with a D3 cultivar with a straw yield of 6 t ha$^{-1}$, compared to a D1 cultivar with a straw yield of 4 t ha$^{-1}$.

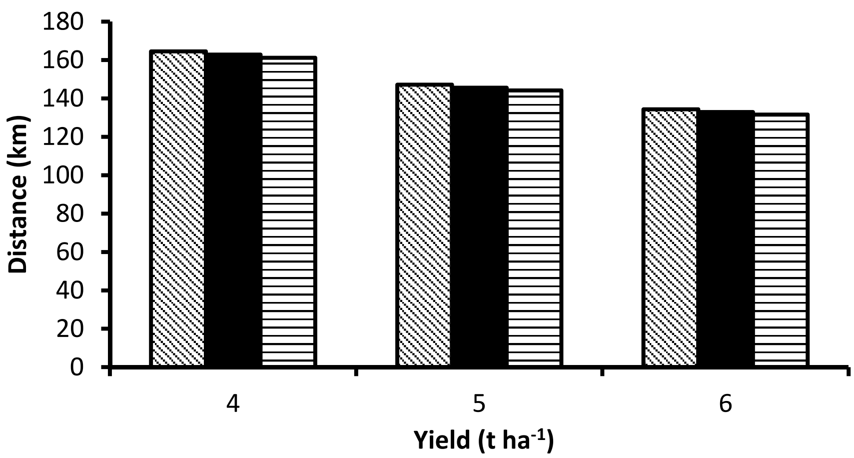


***Figure 11.*** *The average two-way haulage distance for the nine cultivars for feedstock demand of 500,000 t yr$^{-1}$. Digestibility: D1 (diagonally-lined bars); D2 (solid bars); D3 (horizontally-lined bars).*

The costs for delivering 1 tonne of straw, at a demand of 500,000 t yr$^{-1}$ and baseline digestibility (D1) are £13.85, £12.78 and £12.00 for yields of 4, 5 and 6 t ha$^{-1}$, respectively. At the midpoint demand and yield (500,000 t yr$^{-1}$; 5 t ha$^{-1}$), delivery costs are £12.78, £12.67 and £12.56 t$^{-1}$ for yields of D1, D2 and D3, respectively (**Fig. 12a**). The costs for delivering feedstock for 1,000 litres bioethanol, at the baseline digestibility (D1) are £41.87, £38.65 and £36.28 for yields of 4, 5 and 6 t ha$^{-1}$, respectively (**Fig. 12b**). Increasing yield from 4 t ha$^{-1}$ to 6 t ha$^{-1}$ leads to a 13.35% reduction in costs. At the midpoint yield (5 t ha$^{-1}$), delivery costs for feedstock for 1,000 litre bioethanol are £38.65, £37.38 and £36.19 for yields of D1, D2 and D3, respectively. Increasing digestibility from D1 to D3 leads to a 6.34% reduction in costs. The percentage change in *transport costs* as digestibility increases is greater than the percentage change in *transport distance* as digestibility increases. This is because the reduction in cost is a combination of the decreasing distance, and the reduction in the amount of feedstock required, which requires fewer truck journeys, to produce the biofuel. Hence, although the reductions in distances were very small with increased digestibility, the reductions in costs were more significant. When both straw yield and digestibility are increased from the lowest values to the highest values (i.e. from 4 t $ha^{-1}$ at D1 to 6 t $ha^{-1}$ at D3), the costs decrease by 18.84%.

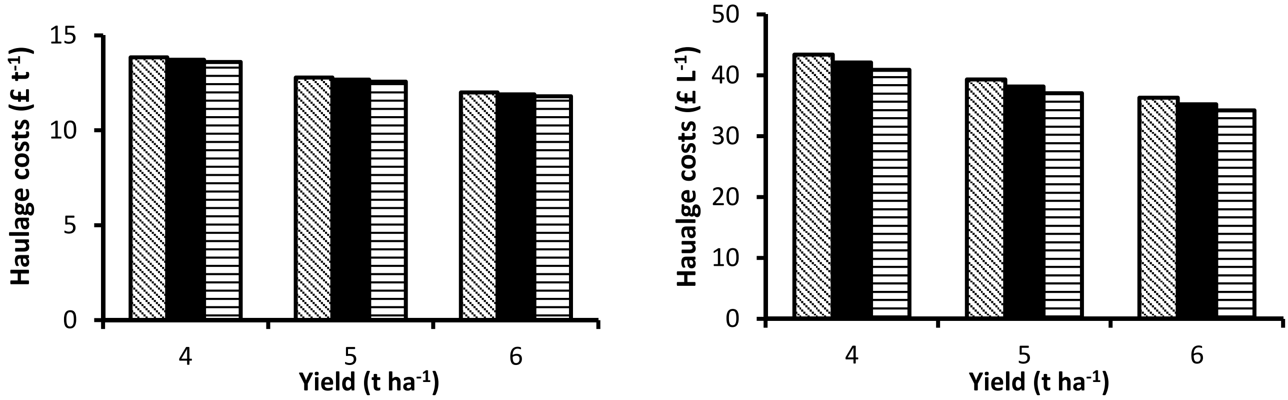


***Figure 12a, b.*** *The haulage costs for **a**) 1 tonne straw and **b**) the straw mass required to produce 1000 L bioethanol for the nine cultivars for feedstock demand of 500,000 t $yr^{-1}$. Digestibility: D1 (diagonally-lined bars); D2 (solid bars); D3 (horizontally-lined bars).*

### 4.4. Environmental impacts

The results for the A1 model are given in **Table 4**. Due to the LCA design the environmental burdens did not vary with straw yield. However, the area of land required to produce the feedstock decreases with the increasing yield. For a 4 t $ha^{-1}$ yield, bioethanol production was 1.21 L $m^{-2}$ agricultural land. This increased to 1.51 L $m^{-2}$ and 1.81 L $m^{-2}$ for yields of 5 t $ha^{-1}$ and 6 t $ha^{-1}$. There were differences between digestibility levels with a 2.32% reduction in all emissions for D2 compared to D1, and a 4.64% reduction in all emissions for D3 compared to D1. N fertiliser production contributed 36% of total GHG emissions with a further 29% from the direct emissions associated with N fertiliser use (**Fig. 13**). The transportation of straw contributed 17%. The transport stage is responsible for the largest contribution to ozone-depleting emissions as well as photochemical oxidant formation and terrestrial ecotoxicity. Direct emissions associated with N fertiliser use are responsible for the majority of terrestrial acidification and marine eutrophication.

***Table. 4:*** *Environmental burdens for the A1 allocation scenario, for the three digestibilities (D1, D2 and D3).*

| Impact category | Units | D1 | D2 | D3 |
|---|---|---|---|---|
| Climate change | g CO2-eq | 189.6 | 185.2 | 180.8 |
| Ozone depletion | mg CFC-11-eq | 0.014 | 0.013 | 0.013 |
| Photochemical oxidant formation | g NMVOC | 0.61 | 0.60 | 0.59 |
| Terrestrial acidification | g SO2-eq | 1.95 | 1.91 | 1.86 |
| Freshwater eutrophication | g P-eq | 0.070 | 0.069 | 0.067 |
| Marine eutrophication | g N-eq | 2.85 | 2.79 | 2.72 |
| Terrestrial ecotoxicity | g 1,4-DB-eq | 0.014 | 0.014 | 0.014 |
| Freshwater ecotoxicity | g 1,4-DB-eq | 0.498 | 0.487 | 0.475 |
| Marine ecotoxicity | g 1,4-DB-eq | 0.618 | 0.604 | 0.590 |
| Water depletion | L | 0.88 | 0.86 | 0.84 |
| Fossil depletion | g oil-eq | 38.46 | 37.57 | 36.68 |

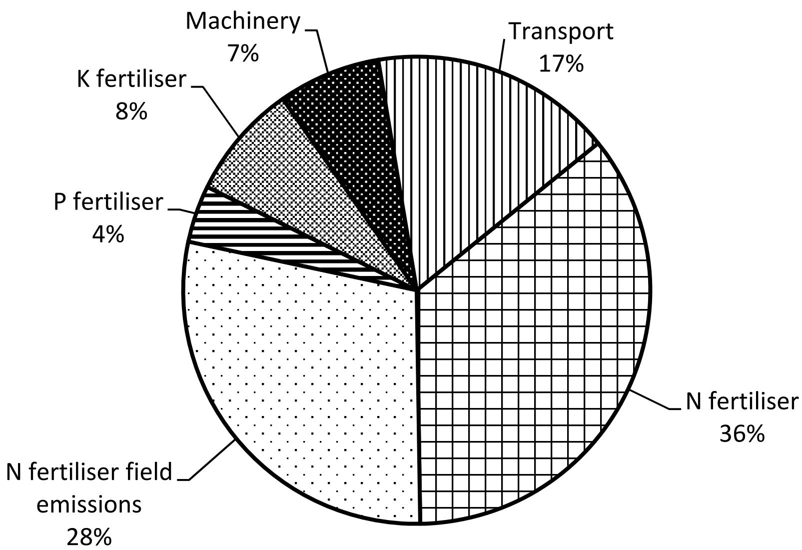


***Figure 13.*** *Contribution of each component to overall GHG emissions for straw production and delivery. N fertiliser (crosshatch); N fertiliser field emissions (spots); P fertiliser (horizontal bars); K fertiliser (light shading); machinery (dark shading); transport (vertical lines).*

All measured emission categories, apart from water use, are lower for A1 compared to the reference system. GHG emissions are 75.1% lower leading to a 17.2% reduction in the GHG emissions for the production of ethanol when A1 is substituted into the reference system. The other emissions range from 94.0% reduction for terrestrial acidification to a 9.4% increase for water use. The differences in overall emissions for producing ethanol from the D1 and D3 cultivars are very small with the biggest difference being only 0.54%. This suggests only very minor reductions in emissions can be achieved by increasing digestibility.

For the A2a allocation scenario, for all EBs except water use, values were lower than the reference system. Ozone-depleting emissions were approximately the same for both systems but the reduction in EB for the other categories ranged from 7.3% for fossil depletion to 86.3% for terrestrial acidification. When the overall emissions for the production of bioethanol are considered, for the 4 t $ha^{-1}$ D1 cultivar, allocation by price reduced GHG emissions relative to the reference system by 10.8%. Other environmental burdens were lower except water use.

EBs for A2a were higher than those in A1. GHG emissions were 111.8% higher and terrestrial ecotoxicity was ten times higher. There were only small reductions in EBs when yield was increased. For increases in straw yield from 4 t to 5 t $ha^{-1}$, EB reductions ranged from 0.68% to 2.42%, with a 1.20% reduction in GHG emissions. For increases in straw yield from 5 t $ha^{-1}$ to 6 t $ha^{-1}$, reductions in EBs ranged from 1.00% to 3.08%, with a 1.85% reduction in GHG emissions. Reductions in EBs from increasing digestibility were even smaller; increasing digestibility from D1 to D2 for the 4 t $ha^{-1}$ straw yield decreased EBs by between 0.13% and 0.60%, (0.31% for GHG emissions) and between 0.24% to 0.68% (0.41% for GHG emissions) from D3 compared to D2.

When allocation is based on gross margins (A2b) instead of price allocation (A2a) EBs were between 34.1% to 41.7% lower. GHG emissions were 38.3% lower for the A2b allocation scenario than the A2a allocation scenario. EBs were still higher than the baseline scenario (A1) with most EBs being approximately 30–50% higher. As with A2a, ecotoxity was considerably higher than the baseline scenario. Increasing yield led to minor decreases in EBs. Unlike with the other allocation scenarios, increases in digestibility actually increases EBs. This is because the increase in allocation of EBs with the increased gross margins from higher digestibility is greater than the EB reduction achieved from a greater ethanol yield. This gives the impression that it is becoming less efficient but this demonstrates an issue with using allocation in this way; if grain was included then you there would be a reduction in EBs associated with the grain as straw digestibility increases as more of the EB are allocated to the straw. This is an example of why system expansion is often preferential to allocation when calculating EBs from multiple product output systems.

Allocation by mass (A2c) approximately doubled EBs relative to allocation by price (A2a). The allocation method maintains the percentage difference between the digestibility levels but the difference between the yield levels is much larger, decreasing 6.86–8.69% between the 4 t $ha^{-1}$ and 5 t $ha^{-1}$ levels, and 10.29–13.65% between the 4 t $ha^{-1}$ and 6 t $ha^{-1}$ levels. GHG gas emissions were 7.42% and 11.32% lower for these differences in yield level, respectively. In general, these values are higher than the reference system. When these values are substituted into the model there is a 6% increase in GHG emissions for the production of 1 litre of ethanol. Some impact categories are much higher such as a 24% increase for marine ecotoxicity and a 22% increase for freshwater eutrophication. However, some emission categories are lower including terrestrial acidification, marine ecotoxicity and terrestrial ecotoxicity.

Allocation made a large difference to the EBs. GHG emissions were greatest for the allocation by mass scenario (A2c) whilst for the other allocation scenarios they were lower relative to the reference system (**Fig. 14**). Ozone-depleting emissions were much higher for the allocation by mass scenario than the other allocation scenarios; they were lowest for allocation by gross margin (A2b) and treating straw as a by-product (A1). For allocation by price (A2a) the emissions were approximately the same as the reference system; the reason for the similar result could be due to the absence of the transport stage in the reference system and as the transport stage was a large source of ozone-depleting pollutants its absence could lead to a large reduction in these emissions. Water depletion was highest for the allocation by mass scenario.

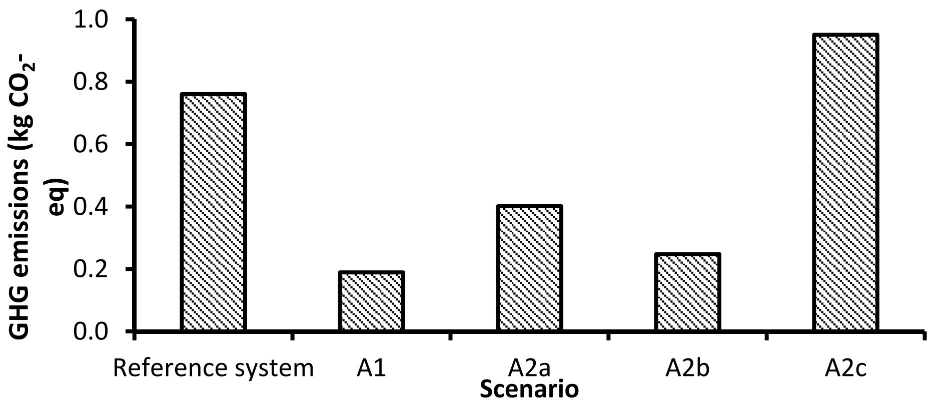


***Figure 14.*** *GHG emissions for the straw production stage for producing straw for 1 L of bioethanol for the four allocation scenarios and reference system. Straw yield = 4 t $ha^{-1}$; Digestibility = D1.*

### 4.5. Survey

The survey received 516 usable responses from farmers that grew wheat (25.8% of the total sample population). Of the 516 responses that were used in the analysis, most were missing at least one piece of data (e.g. answered a question with N/A) but were included in the analysis as it would have greatly limited the data to exclude all these responses. The responses were tested to see if there was nonresponse error and/or error resulting from coverage error as well as to determine how representative the data is of the farming population of the areas sampled. The data was compared to data known *a priori* from the Defra June survey for 2012. From this it can be seen that the survey response farms are much larger on average than in the general population meaning that the survey is biased towards larger farms. The survey did not differentiate between farm sizes and holding sizes so this goes some way to explain the larger farm size in the current survey. However, even considering this, it is clear that larger farms are over-represented in the responses. This means that the findings are not representative of the farmer population as a whole but are likely to be more representative of the farmed area.

### 4.5.1. Important characteristics

With respect to important cultivar characteristics, 95% and 97% of respondents, respectively, rated *potential gross margin* and *grain yield* as important or very important; however, 73% of respondents rated *potential gross margins* as very important and 67% of respondents rated *grain yield* as very important. For both *resistance to lodging* and *resistance to disease* 90% of respondents gave a rating of important or very important. Furthermore, 57%, 53% and 51% of respondents rated *customer preference and contractual requirements*, *seed cost and availability* and *crop timing constraints* as important or very important, respectively.

The ratings for the characteristics were compared between groups. In general there were very few differences between groups. For ‘other’ farm types *customer preferences and contractual requirements* were more likely to be rated as neutral than expected. For farm size, farms under 100 ha were much more likely to have a neutral opinion of *potential gross margins* than expected. For farmer age, there was a trend for more farmers than expected over 65 years old to rate *disease resistance* as very important. For region, respondents in the South East were more likely to see *grain yields* as neutral and *customer preferences and contractual requirements* as important. Respondents in the North East recorded *crop timing constraints* as more important, which could be explained by the lower workability window in the North East (Rounsevell & Jones, 1993). Respondents who grew all feed wheat were more likely to rate *grain yield* as ‘very important’ than those who grew all milling wheat ($P$ = 0.002).

### 4.5.2. Information for cultivar selection

With respect to cultivar selection, 89% of respondents stated that their *own knowledge and experience* was important or very important in choosing which cultivars to grow. This was followed closely by the use of *AHDB RLs* with 88% of respondents noting they were important or very important for their selection of cultivars. However, slightly more respondents gave the *AHDB RLs* the ‘very important’ rating (41.3% compared to 39.7%). 82% of respondents rated *advice from agronomists* as important or very important. 57% stated that *customer preference and specification* was important or very important whilst only 37% said that *word-of-mouth* was important or very important. Most respondents rated multiple information sources as important or very important. 31% chose three sources, 34% chose four and 19% chose five. When respondents who grew all feed wheat were compared to those who grew all milling-quality grain, respondents who grew all milling-quality grain were significantly more likely than expected to rate *customer preferences and* *contractual requirements* as very important whilst those who grew all feed wheat were more likely to rate it as neutral.

The ratings for the characteristics were compared between groups. In general there were very few differences between groups. For farm type, ‘other’ farms more likely to be neutral to *own knowledge and experience* and *customer preference and contractual requirements*. For farm size, farms over 300 ha were more likely to cite *AHDB RLs*, *own knowledge and experience*, *advice from an agronomist* and *customer preference and contractual requirements* as very important. Based on the number of ratings for neutral, important and very important, the number of very important responses increased with farm size suggesting that larger farms are using a greater number of information sources for their decisions. Ratings did not significantly differ between farmer age groups. For region, *customer preference and contractual requirements* was more important than expected for the South East. This is likely to be because a greater proportion of milling wheat, in particular nabim group 1 cultivars, is grown in the South East (AHDB, 2013).

#### 4.5.3. Wheat straw use

Of the 97,958 ha of wheat covered by the survey results, 53,475 ha (54.6%) was chopped and incorporated, 8,536 ha (8.7%) was baled for on-farm use, and 32,897 ha (33.6%) was sold either baled or in the swath (**Table 5**). The remainder (3,050 ha; 3.1%) was used for other uses such as for covering carrots and straw-for-muck agreements. Most of these uses eventually returned the material to the field.

***Table 5.*** *Straw use per region (ha) and the percentage for each use in each region in parenthesis.*

| Region | Sold | Chopped | On-farm | Other | Total |
|---|---|---|---|---|---|
| East Midlands | 8,276 (34.2%) | 11,860 (48.9%) | 3,120 (12.9%) | 976 (4.0%) | 24,232 |
| East of England | 10,688 (27.5%) | 25,224 (64.8%) | 1,906 (4.9%) | 1,078 (2.8%) | 38,896 |
| North East | 1,594 (62.0%) | 555 (21.6%) | 411 (16.0%) | 11 (0.4%) | 2,571 |
| South East | 4,918 (26.2%) | 6,698 (49.4%) | 1,767 (13.0%) | 186 (1.4%) | 13,569 |
| Yorkshire | 4,360 (38.9%) | 4,931 (44.0%) | 1,122 (10.0%) | 799 (7.1%) | 11,212 |
| Total | 17,937 | 53,475 | 8,536 | 3,050 | 97,958 |

Of the straw sold, 149 farms sold all of the straw in the swath (47.0%) whilst 145 farms sold all of the straw as baled (45.7%). The remaining 23 farms sold their straw as a mixture of baled and in the swath (7.3%). Of the straw sold, 17,752 ha went to the livestock sector, 135 ha went for industrial uses, 5,519 ha went for bioenergy and 9,492 ha went to unknown markets. 144 farms baled straw for use on the farm (27.9%). The average proportion of straw baled for use on these farms was 49.5%. 43 of these farms used all of the straw on-farm. Almost all of these farms had sizeable livestock populations on the farm. On 103 farms all the straw was chopped and incorporated whilst on 208 farms none of the straw was chopped and incorporated. The focus of the analysis is the amount of straw chopped and incorporated as this represents the pool of straw that is available for exploitation should a new market for straw emerge.

***Region***

The East of England had the highest proportion of straw chopped and incorporated, followed by the East Midlands and the South East (**Fig. 15**). The North East had the lowest proportion. A much greater proportion of straw is sold in the North East than the other regions. Other uses of straw are fairly low or, in the case of the North East, none goes to other uses. Only a small sample size was used from the North East so it is unclear how representative this data are.

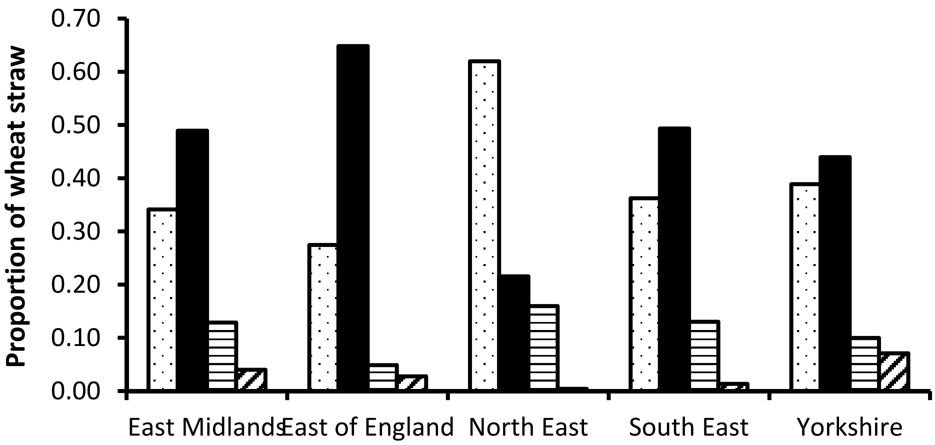


***Figure 15.*** *Mean percentage uses of straw for each region. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).*

The proportion of farms chopping all of the straw varied with region (*P* <0.001) as did the proportion of farms baling all of their straw (*P* <0.001). Farms in the East of England had the lowest proportion of farms baling all of the straw and the highest proportion of farms chopping all of the straw. Yorkshire and the North East had the highest proportion of farms baling all of the straw and the lowest proportion of farms chopping all of the straw. Of the remaining farms there was not a significant difference in the proportion of straw chopped between regions (*P* = 0.115) suggesting that differences in the amount chopped between regions are determined by the farms that chop all or none of the straw. However, the large difference in the proportion of straw chopped between Yorkshire and the North East suggests there are differences between these two regions. Finding significant differences may be difficult because of the small number of samples for the North East.

***Farm size***

The use of straw for each farm size category is given in **Fig. 16**. The data suggests that the proportion of straw that is incorporated tends to increase with increasing farm size. To consider why the proportion of straw chopped and incorporated increases with farm size, the proportion of the farms that chopped all their straw and those that chopped none of the straw were examined. The proportion of farms chopping all of their straw does not significantly vary with farm size grouping (*P* = 0.707). However, the proportion of farms chopping none of their straw (i.e. baling all of the straw) does significantly vary with farm size grouping (*P* <0.001). The proportion of farms baling all of the straw is similar for farms up to 250 ha in size; the proportion of farms baling all the straw for farms above this size is lower. So the number of farmers that chose to incorporate all straw is even across farm size but the number of farmers that chose to incorporate no straw varies with farm size, with farms over 249 ha less likely to incorporate no straw.

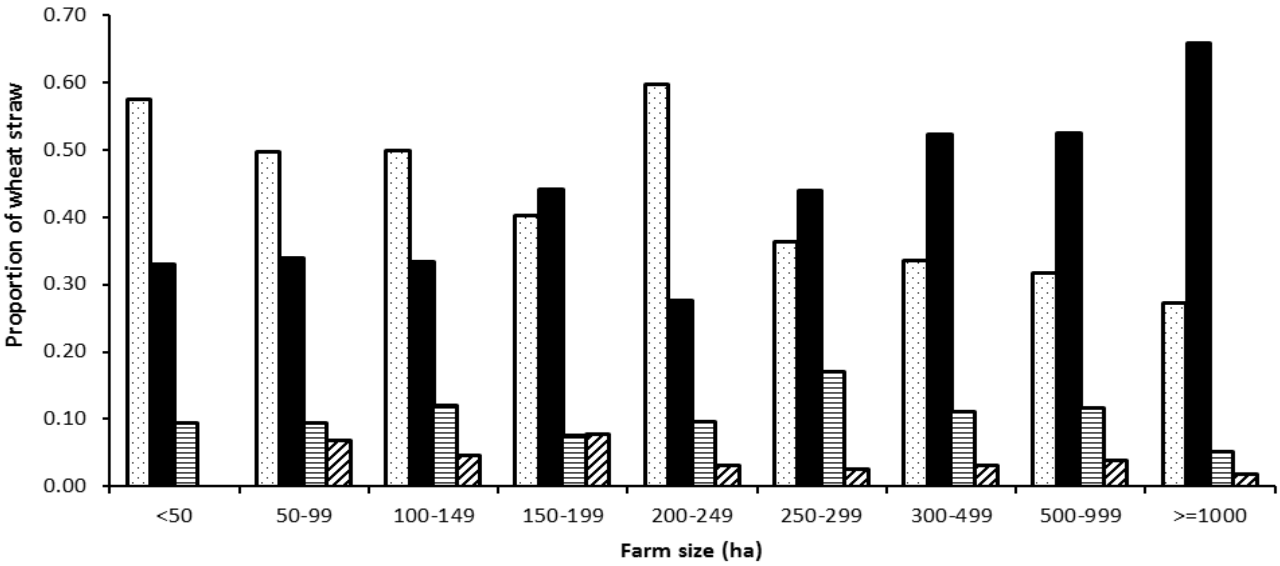


***Figure 16.*** *Mean percentage uses of straw for each farm size category. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).*

The proportion of straw chopped and incorporated was compared between farms that baled only a proportion of the straw (i.e. excluding farms that chopped all straw or none of the straw) for the aggregated farm size categories. The difference between groups was just above the 5% significant level (*P* = 0.051) with farms between 100 and 299 ha having the lowest rate of incorporation, farms 0–99 ha and 300–499 ha having intermediate rates of incorporation and farms 500 ha and above having the highest rate of incorporation. The higher straw incorporation rates for larger farms appears to be a result of more farms chopping and incorporating all the straw as well as a lower proportion of straw being baled on the farms that were baling straw.

***Farmer age***

The use of straw by each age category is given in **Fig. 17**. Excluding the 35–44 year old age category, the proportion of straw chopped and incorporated increased with age whilst the proportion of straw tended to decrease. Straw use for the 35–44 year old age group does not fit this pattern with very high rates of straw incorporation and low a lower proportion being sold. The proportions baled for on-farm use and for other uses are low for all age categories.

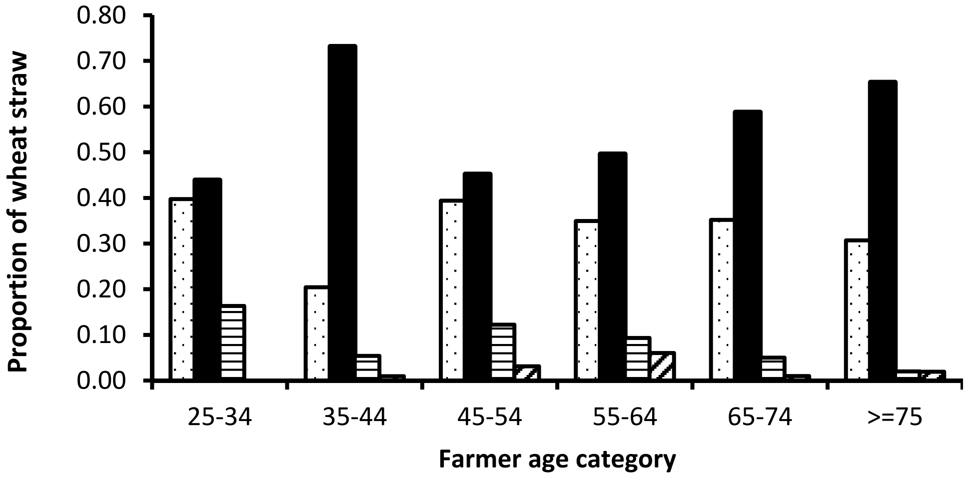


***Figure 17.*** *Mean percentage uses of straw farmer age categories. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).*

To consider why the proportion of straw chopped and incorporated varies with farm type, the proportion of the farms that chopped all their straw and those that chopped none of the straw were examined. The proportion of farms chopping all of their straw significantly varies with farmer age category ($P$ = 0.014) with the proportion of farms chopping all the straw tending to increase with farmer age; however, the 35–44 year old age group does not fit this trend with a much larger proportion of straw chopped and incorporated. The proportion of farms baling all of their straw varies with farmer age ($P$ = 0.011) but there is not a pattern with increasing age. For the remainder of farms, the proportion of straw chopped and incorporated does not vary with farm type ($P$ = 0.131).

***Farm type***

The use of wheat straw for each farm type is given in **Fig. 18**. Cereal farms had the highest proportion of straw chopped and incorporated, followed by general farming and other farm types. The proportion of straw sold was similar for cereal and general farming, with much lower amounts for other farm types. Other farm types used the majority of their straw for on-farm uses.

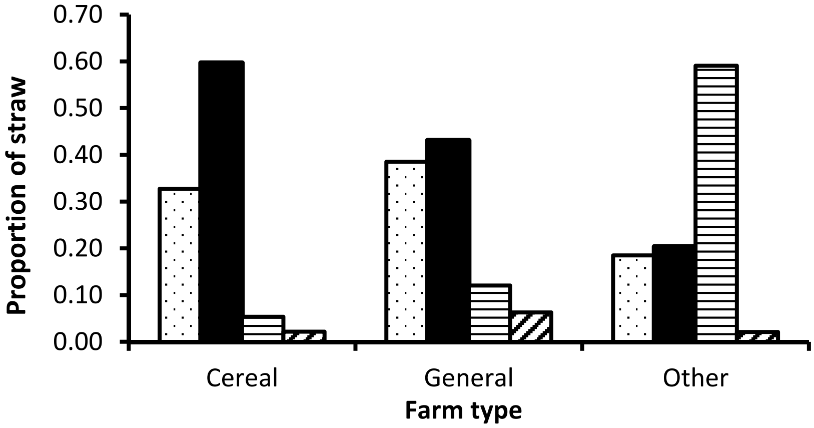


***Figure 18.*** *Mean percentage uses of straw for three farm types. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).*

To consider why the proportion of straw chopped and incorporated varies with farm type, the proportion of the farms that chopped all their straw and those that chopped none of the straw were examined. The proportion of farms chopping all of their straw significantly varies with farm type ($P$ <0.001) with the highest proportion of farms chopping all the straw being cereal, followed by general farming and then other farms. The proportion of farms baling of their straw varies with farm type ($P$ <0.001) with a greater proportion of other farms baling all of the straw than cereal and other farming. For the remainder of farms, the proportion of straw chopped and incorporated does not vary with farm type ($P$ = 0.139).

### 4.5.4. Wheat straw management

Over half (276, 53.5%) of the respondents provided a price for 1 tonne of straw at which they would start managing their straw for increased straw yield. Of the remainder, 21 respondents said they would not manage their straw for any price; 37 said they did not know and, even though it was not given as an option, one respondent said that they already manage their wheat for straw yield. 181 respondents did not answer the question (i.e. ticked N/A).

The average price given was £90.86 but there was a large range of prices (**Fig. 19**). There were a number of very low values (e.g. £10, £15), which were lower than estimated breakeven prices for straw. Other prices were very much higher (e.g. £500, £1,000). The interquartile range was £50 to £100. Price did not significantly vary with farm size ($P$ = 0.994), farm type ($P$ = 0.110) or region ($P$ = 0.210). It did, however, vary with farmer age where price was significantly lower in farmers aged 55 and above compared to farmers younger than 45 ($P$ = 0.015), with farmers aged 45 to 54 asking for an intermediate price.

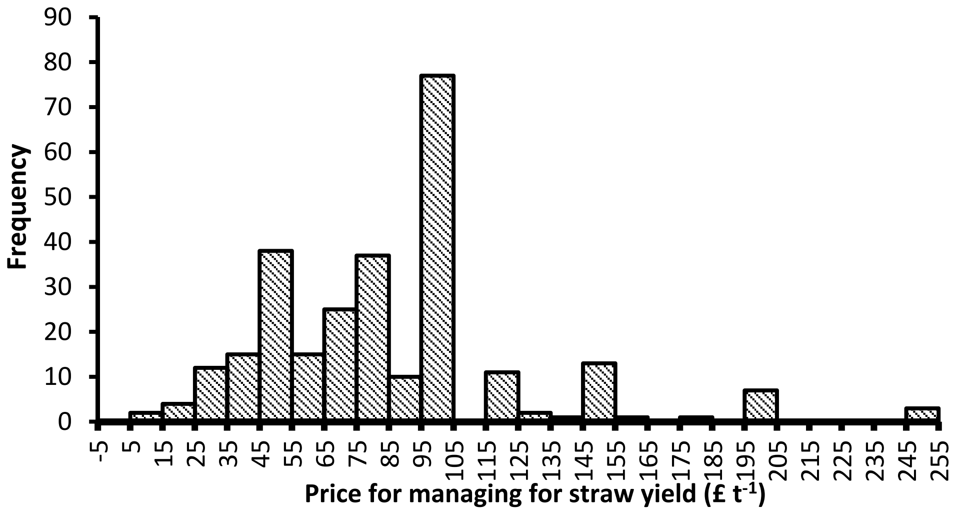


***Figure 19.*** *Frequency chart of prices for managing straw. (N.B. One value for £500 and one for £1,000 are excluded from the analysis.)*

If the straw price reached £100 $t^{-1}$, 231 respondents (44.8%) said they would sell more straw; 121 respondents already used all of their straw; 110 respondents would not sell any extra straw; 45 respondents did not answer the question; whilst nine noted that they did not know (this was not given as an option so a greater number of respondents might have selected this if it had been; **Fig. 20**). The respondents unwilling to sell extra straw had a total of 15,255 ha of incorporated straw (28.5% of all incorporated straw). This suggests that even for a very generous price for straw, significant amounts of straw that could be baled will not be sold.

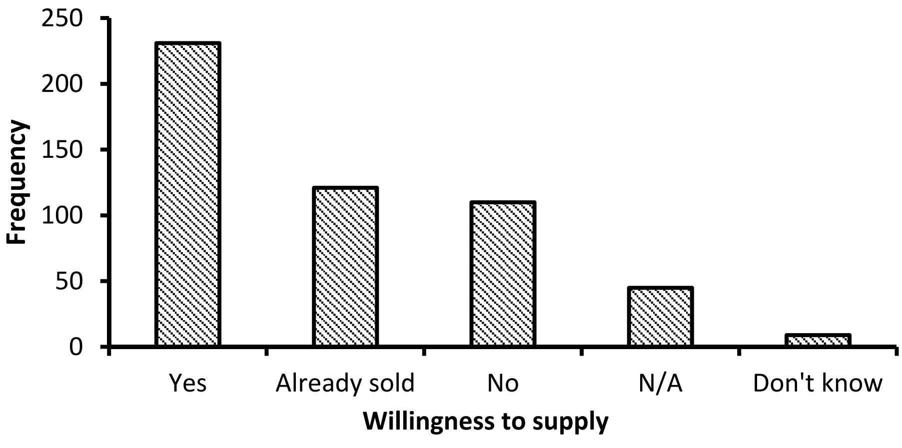


***Figure 20.*** *Willingness to supply extra straw at £100 $t^{-1}$. N/A = not answered.*

When considering farms that had additional straw (i.e. that currently incorporated straw), the likelihood to sell extra straw did not vary with farm type ($P$ = 0.156); however, there was a pattern of other farm types being unwilling to supply more straw. The likelihood to sell extra straw did not vary with farmer age ($P$ = 0.654) or farm size ($P$ = 0.148). Willingness to supply extra straw did not significantly vary with region ($P$ = 0.078); however, there was a trend for farms in the East

Midlands to be willing to sell extra straw with those in the East of England were less willing to sell extra straw.

Question 13 asked which management practices farmers would employ if the price of straw were to increase to £100 $t^{-1}$ or £162 $ha^{-1}$ in the swath. Although the price for selling in the swath does not specify a yield, it is assumed that the farmers will interpret the question as producing a higher yield than they currently do. Of the 381 respondents who answered this question, 114 respondents said that they would not utilise any management practices whilst a small number of farmers (10) responded that they were uncertain what they would do. The remainder answered that they would employ at least one of the management techniques. The responses, excluding respondents who did not answer the question and those who were unsure of the number of management practices that they would use, are given in **Fig. 21**. It is informative to note that 91% of respondents wanting to manage for extra yield rate AHDB RLs as important or very important in question ten.

The intention to utilise new management practices did not relate to farm size ($P$ = 0.225), farm type ($P$ = 0.958), farmer age ($P$ = 0.552), and region ($P$ = 0.211). When incorporating the counts for N/A into the 'None' category, region does become significant ($P$ = 0.023) with the East of England more likely to not use any management practices. However, farm type ($P$ = 0.287), age group ($P$ = 0.578), and farm size ($P$ = 0.135) remain non-significant.

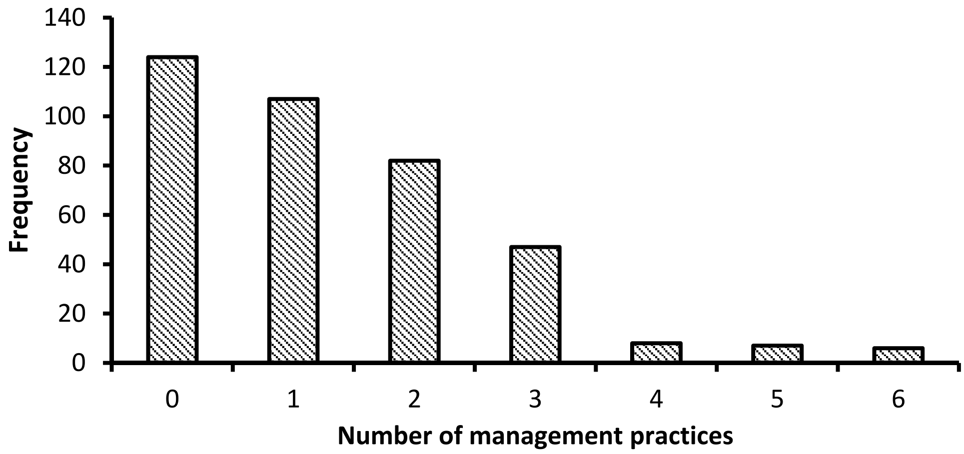


***Figure 21.*** *Number of management practices respondents would use to increase straw yield should the price reach £100* $t^{-1}$.

Changing the cultivar to a higher straw-yielding cultivar was most popular with 206 respondents (40% of all respondents) willing to employ this practice (**Fig. 22**). The other management practices varied from 39 to 80 respondents selecting each. 80% of the times that a respondent selected one of the other management practices they had also selected growing a cultivar with higher straw yield. The methods of choice do not vary with farm size ($P$ = 0.936), farmer age ($P$ = 0.999), farm type ($P$ = 0.203), and region ($P$ = 0.379). A few respondents suggested that they would lower the cutter height to increase straw collection. This may have been selected more frequently had it been given as an option.

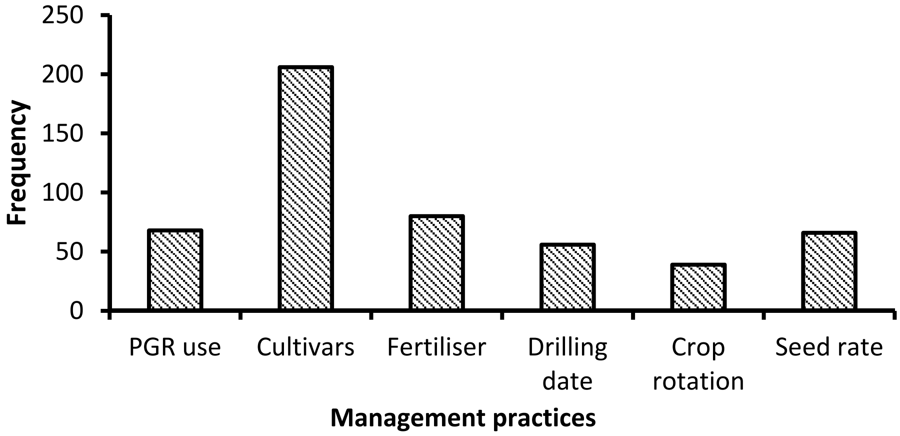


***Figure 22.*** *Number of respondents who would utilise each management practice.*

#### 4.5.5. Attitudes and straw use

The farms were divided into groups based on the amount of straw they incorporated (0%, 1–49%, 50–99%, and 100%). Attitudes to *land stewardship* varied with the amount of straw incorporated ($P = 0.028$); farmers incorporating no straw were more likely to have a neutral attitude to *land stewardship* whilst farmers who incorporated all their straw were more likely to consider *land stewardship* as very important.

Farms were divided into those unwilling to sell extra straw, those willing to, and those who had utilised all their straw already. Respondents who were unwilling to sell extra straw were significantly more likely to rate *land stewardship* and *family objectives and succession* as very important. They were also more likely to rate *quality of life* as very important. *Maintaining the environment* was not significantly different between groups but there was a strong trend for those who were unwilling to supply extra straw to rate it as very important.

## 5. Discussion

### 5.1. Cultivar trials

The results of the current investigation taken together with previous field experiments (from Roy, 2014) demonstrate the variability in grain and straw yields and highlight the difficulty in providing information to farmers on expected straw yields. Straw yields were 70% higher in 2012 than 2011. This variation is higher than in other studies (e.g. 22% yearly variation in Larsen et al., 2012), which is likely due to differing weather conditions between the experimental years. In 2011, a dry spring meant that average straw yields in England were lower than normal (Banham, 2011). In general, the results of the three growing seasons have to be taken in the context that the weather was atypical. For example, the summer in 2012 was the second wettest year on record with the highest rainfall for April and June ever recorded (Anon, 2013b). This was in strong contrast to the previous two summers where rainfall was low.

Grafton had the shortest stem yet did not have a significantly different stem yield than the other cultivars. Of the three cultivars, Grafton had the greatest yield for the lower parts of the stem (S1) but the lowest yield for the upper stem (S4). It could be that as a shorter cultivar Grafton has a denser lower stem, which meant that even though it was shorter, it still had a similar amount of stem material. Another possibility for stem yield not being significantly different than Xi19 is that the greater ear number of Grafton compared to Xi19 meant that although the stems were lighter, the greater number meant that weight did not significantly differ between the cultivars.

The stem sections were compared to see how the mass of material changes up the plant and also to see the influence that cutter bar height will have on the total amount of material collected. The data shows that the influence of cutter bar height depends on the PGR treatment and cultivar. Also, having a significant difference between cultivars depends in part on cutter bar height, with some differences between treatments only seen for straw that had the lower part removed.

Average straw yields (stem without both the bottom 10 cm and the leaf blade for a PGR treated plot) are 4.71, 4.37 and 4.77 t $ha^{-1}$ for Cordiale, Grafton and Xi19, respectively. These fit in the UK straw yield range given by Nix (2013) and ABC (2013) and are close to the average yields for straw used at Ely straw-burning power station (Newman, 2003). However, they are considerably higher than those estimated by Glithero et al. (2013a) based farm survey responses of bale number and size per hectare.

Xi19 showed greater variability in grain yields than Grafton and Cordiale. Xi19 was removed from the AHDB RLs after 2010–11 as use dropped to less than 2% of the cropped area. However, the reasons for this appear to be because it was lodging prone if planted too early, difficult to achieve milling specification and a possibility of above-average sterility (pers. comm. Bill Handley, AHDB). As the plots in this project were only minimally affected by lodging, this does not explain why Xi19’s yields were lower than expected and more variable.

Results from the field experiments suggest that modern cultivars do not necessarily differ in straw yield. In the 2009–2010 and 2010–2011 field experiments (Roy, 2014) the only difference was for Maris Widgeon, which is an older non-semi-dwarf cultivar. Larsen et al. (2012) found a significant difference between cultivars in their assessment of straw yield of modern wheat cultivars, which suggests that finding differences between modern cultivars depends on which cultivars are being compared.

The small differences in total straw yield between cultivars, taken together with the high variability in total straw yields across years, suggest that being able to provide accurate straw yield data for cultivars as part of a RL might prove to be difficult. For the AFBI barley RLs, the winter cultivars are placed in four straw yield categories ranging from low (less than 3.75 t $ha^{-1}$) to high (greater than 4.5 t $ha^{-1}$). The range of straw yields for wheat appear to vary much less than barley; this means that should metrics be included in future RLs, these could potentially take the form of only two straw yield categories, high and low.

There is little data considering the impact of chlormequat on straw yields. In this study there was a non-significant trend for reduction in stem yield with the application of chlormequat, which is in contrast to the large reduction in stem length that chlormequat application caused. However, the reason for the non-significant difference might be because the lower stem appeared to be denser for the chlormequat-treated plots, making up for the decrease in stem length. When the bottom 10 cm stem is not included in the stem yield the difference between the treated and non-treated plots increases but is still not significantly different. However, increasing the simulated combine header height to 15 cm resulted in a significant reduction in stem yield with the application of chlormequat; this suggests that chlormequat-induced reductions in stem yields might only be realised in baled straw yield when the cutter height is set to 15 cm or above, potentially lowering the straw available for biofuel production. The reason for the lack of significance in previous studies might be due to the way that straw was collected, in particular if the straw was being collected to ground level.

Previous studies have found variable influences on grain yields from the application of chlormequat. In this study, the combine-collected and quadrat grain samples differed in how they responded to chlormequat, though this appears to be the result of variability in the data. There was a pattern of increasing HI with chlormequat application; however, it was a small difference. This is due to the HI being calculated using the quadrat samples, where the grain yield did increase. Calculating the HI with the combine-collected samples will give different results. The application of chlormequat led to a non-significant increase in HI through its increase in grain yields and a non-significant decrease in straw yield.

As expected, the SFWS varied with cultivar and PGR application, with failure wind speed decreasing with increasing height. Xi19 was most susceptible to lodging followed by Cordiale and Grafton which matches the ranking from AHDB’s 2010–2011 Recommended Lists. The values for stem lodging fall in the range of wind speeds found by Berry et al. (2003a); however, RFWSs are much higher than those seen in the same study. Stem lodging risk was consistently higher than root lodging with the difference between the RFWS and SFWS of samples ranging from 1.31 m $s^{-1}$ to 16.21 m $s^{-1}$. This large variability in differences between these failure wind speeds results from a large range of rooting depths and root plate spreads, as well as a large range of values for leverage on the root system, which is partly the result of variability in ear number.

PGRs on average led to a reduction in SFWS of 1.28 m $s^{-1}$, which compares favourably to Berry et al.'s (2003a) figure of 1.4 m $s^{-1}$. The increase in failure wind speed with the application of chlormequat was lowest for the tallest cultivar (Xi19) even though the reduction in plant height was greatest for this cultivar (92 mm compared to 82 mm and 65 mm for Cordiale and Grafton, respectively). Despite the greater height reduction, the reduction in the HCG resulting from the application of chlormequat was the same for Cordiale and Xi19 (50 mm). At the same time, although it was not significant, the internode material strength of Xi19 decreased slightly with the application of chlormequat whilst that of Grafton and Cordiale increased. It appears that the non-significant decrease in material strength, combined with a reduction in HCG only equal to Cordiale, led to a lower increase in SFWS with the application of chlormequat for Xi19.

Chlormequat did not have a significant influence on RFWS but there was a general pattern of increasing failure wind speed with the application of PGRs. Overall, the average increase in RFWS with the application of chlormequat was 1.77 m $s^{-1}$, which is similar to that seen in Berry et al. (2003a). There are limited studies investigating the influence of chlormequat on stem and root characteristics. Berry et al. (2000) found chlormequat slightly reduced material strength but it was not found in the current study. PGRs did influence some of the characteristics of the lower internodes (increasing breaking strength and decreasing length of internode 2) but not the others. PGRs did not significantly influence root traits, which is in accordance with other studies (e.g. Berry et al., 2000).

Nitrogen treatments only had an influence on a few of the traits assessed. The lower stem (S1) mass and leaf mass were influenced by N treatment and the reason for these effects is unclear. For the lower stem, the intermediate N treatment had the highest yield. It would be expected that increased N application would increase both stem and leaf mass yet this was not found in the current study. N application did not influence lodging susceptibility or stem and root characteristics. When differences in lodging susceptibility between N treatments have been found in the literature this was in response to larger differences in N application (e.g. 160 kg $ha^{-1}$ and 240 kg $ha^{-1}$ used by Crook & Ennos, 1995). As with other comparisons between N treatments, the lack of significance could be a result of only a small range of N fertiliser level used in this study or due to a low availability or delayed uptake of additional N. The N treatment might not have been as effective as intended due to the weather and the timing of the final N application. Significant amounts of N might have been made available in the soil from high rainfall in April leading to nitrogen mineralisation giving the plants more N than they required and, therefore, masking differences in the amounts of N applied later on. Another issue could be that as after the final N application there was only limited rainfall until early June, the N fertiliser (ammonium nitrate prills) might not have been dissolved into the soil and, therefore, might not have been available to the plants until after the stem growth phase.

The majority of studies of wheat straw digestibility have found significant differences between cultivars. The results of this study support that there are differences between cultivars with two of the cultivars differing significantly. The results also support work (e.g. Zhang et al., 2014) showing that leaf material is more digestible than stem. It did not support that the lower stem is less digestible than the upper stem; however, the leaf sheath was included in these assessments which may have masked a difference in the stem. The results were lower than values found in Roy (2014) though it is unclear why this was.

The reason for the differences in digestibility does not appear to be explained by the proportion of biomass made up of glucose as Xi19 had a far higher glucose proportion than Cordiale and Grafton yet had an intermediate digestibility. Previous literature supports that there is not a relationship between glucose content and digestibility (e.g. Roy, 2014). The straw from Cordiale and Grafton was kept in storage for about six months longer than Xi19 which could potentially have had an influence on the sugar yields.

There are limited studies investigating the influence of PGRs on straw digestibility. Roy (2014) found that chlormequat did not increase digestibility. One cultivar, Cordiale, assessed in the current study was assessed in Roy (2014) and was found not to significantly increase with chlormequat application. This study suggests that chlormequat-application can have an influence on digestibility though there was considerable variation. It is unclear why chlormequat application did not significantly affect digestibility in the previous field experiment (Roy, 2014). The specific conditions during the application of chlormequat may have had an influence as it can have variable effects on plant form depending on the timing and mode of application, and the weather conditions (e.g. Baker & Hunt, 1985).

It is unclear why the application of chlormequat increased digestibility for this study. It was hypothesised that chlormequat might increase digestibility by increasing the leaf-to-stem ratio; however, when the leaf and stem were analysed separately, there was still an increase in digestibility with PGR application. For the majority of the assessments, PGR led to an increase in the proportion of biomass that is glucose suggesting that the greater release of sugars after pretreatment is due to there being a greater proportion of glucose in the material. These higher glucose amounts could have been due to delayed senescence; chlormequat has been shown to delay flag leaf senescence in triticale (Naylor, 1989) and canopy senescence in barley (Green et al., 1985). However, for the whole plant Xi19, the proportion of glucose was the same with and without chlormequat but the digestibility was higher for the material that had chlormequat applied. The amount of sugar in the material does not necessarily relate to the sugars released after digestion as the leaf material was shown to have the lowest sugar proportion but had the highest digestibility.

As only three cultivars were assessed it was difficult to compare the plant height and digestibility. It did not appear that there was a relationship between height and digestibility as the shortest and tallest cultivars did not differ significantly in digestibility. This does not support the finding of Roy (2014) and Jensen et al. (2011) who found that digestibility decreased with increasing plant height. However, Roy (2014) used more cultivars with a greater range of heights and a relationship was strongly influenced by strong leverage on the correlation from the taller plant (Maris Widgeon).

### 5.2. Economics

The economic model gave a breakeven price for baled straw of £31.38 $t^{-1}$, which is lower than the £55.50 $odt^{-1}$ calculated by ADAS (2008) but higher than the £22.58-23.37 $t^{-1}$ calculated by Banham (2011). The ADAS value was greater due to higher fertiliser prices. The straw breakeven price calculated by Banham (2011) had higher prices for $P_2O_5$ and $K_2O$ but was lower than the breakeven price calculated in the current study as it did not include other fertilisers and had lower contractor's fees. MAFRA (2014) suggested a 15% premium for farmers, which would increase the minimum breakeven value of £36.09 $t^{-1}$. The current price of straw suggests that farmers are getting a larger premium than 15%, though this might be due to supply and demand balance. However, for other farmers a larger premium is needed to encourage the supply of straw. Glithero et al. (2013b) found that farmers wanted a price of £50 $t^{-1}$, which would be a premium of approximately 60%.

In the swath, the minimum price to sell for was £54.59 for a 4 t $ha^{-1}$ crop, much higher than the £26.83 $ha^{-1}$ for an unknown straw yield in the swath estimated by Banham (2011). This suggests that farmers must take account of the nutrients being removed in the straw when agreeing on a price for selling straw in the swath. The ABC (2013) suggests a standard price of £60 $ha^{-1}$ for straw in the swath. At this price farmers are just above breakeven price. However, farmers might not be selling the straw for profit but to provide better conditions for the next crop. In this case selling the straw for the breakeven price is acceptable.

For straw at a price of £47.38 $t^{-1}$, the straw GM is £16.00 $t^{-1}$. For a 4 t $ha^{-1}$ straw yield, this could increase the overall wheat GM from £761 $ha^{-1}$ to £825 $ha^{-1}$, an increase of 7.8%. The GM relative to price is much lower for straw than grain, suggesting that basing estimates of the benefits of increasing straw yield cannot be made using prices alone and must take account of the GMs for grain and straw. For a price of £100 $t^{-1}$ straw, the GMs for straw are still much lower than those for grain, suggesting that even for a very high straw price straw will only remain a secondary product. In this experimental work the lower GMs of straw as a percentage of straw price compared to grain suggest that the importance of grain and straw should not be based on their prices. However, it should be noted that GMs are not an indication of profit. Depending on the specific conditions, the straw may be more valuable to farmers than the GMs suggest. Whereas grain GMs do not account for the machinery operations required for the production of wheat the straw GMs presented do account for machinery operations with the contractors' prices included in the calculations. Because of this, the straw GMs are in effect a better proxy of profit to farmers rather than grain GMs. In reality, the importance of the sale of straw will vary greatly between farmers. Some will see it as vital part of the budgeting for enterprise choices whilst others will see it as a bonus. Therefore, it is unclear whether straw GMs or prices are the most suitable method for making decisions about crop enterprises. Due to grain having much higher GM than straw, increasing straw yield and digestibility only had a small impact on total wheat GM. To put this in perspective, the data suggests that any increases in GMs achieved by increasing straw yield would be negated by a 2-4% reduction in grain yield. This suggests that from a GM perspective, growing these hypothetical cultivars would not be very beneficial to farmers. If there were potential trade-offs resulting from increases in straw yield and digestibility, such as an increase in lodging susceptibility, then this would quickly outweigh the benefits from the increased straw yield.

Another issue that is unfavourable to the use of cultivars with higher straw yields is the higher costs when straw cannot be baled. In the model it is assumed that a farmer would only grow the higher straw-yielding cultivars if it was going to be baled; however, if the straw could not be baled (e.g. if there was a high rainfall at harvest) then the additional straw would have to be chopped and incorporated. It can be surmised that this higher straw yield would lead to higher costs for chopping and incorporating the straw and could potentially exacerbate any potential problems resulting from the retention of straw. Issues, such as weed problems from surface crop residue preventing herbicides reaching the soil surface, are more likely to occur with higher straw yields when they are chopped and incorporated (Midwood & Birbeck, n.d.).

The trade-offs and potential higher chopping fees, taken with the only small increase in wheat GMs from growing cultivars with higher straw yields, strongly suggest that farmers would need to be given an incentive to grow these cultivars on top of the additional GM increases from the higher straw yields. The digestibility premium would likely have to be higher than the percentage increase in ethanol that results from higher digestibility.

Work with the hypothetical cultivars suggests that digestibility premiums would only make a small difference to overall cultivar value and straw yields would have only a small influence on GMs.

Further work is needed to quantify the potential value of DPCs. To consider the breeding of future crops an optimisation model could be used to determine the best partitioning of yield between straw and grain at different straw and grain prices. This would require a better understanding of the relationships between the traits (i.e. the trade-offs).

### 5.3. Logistics

The use of DPCs with higher straw yields and digestibilities has the potential to reduce the area required for meeting a SGB biorefinery's feedstock demand. Increasing straw yield leads to large reductions in transport distances and suggests that there are logistic, economic and environmental transport benefits to increasing straw yields. The distance savings from increasing digestibility are small; however, increasing digestibility decreases the amount of straw required to meet a specific ethanol output and, therefore, cost savings are greater than suggested by the reduction in distance. Increasing both digestibility and yield could reduce haulage costs by almost 20%. The extent of the haulage cost savings of increasing straw yield and digestibility depend on feedstock demand, the proportion of land supplying straw and the road tortuosity. Increasing feedstock demand or $\tau$ increases transport costs but the benefits of using cultivars with higher straw yield and digestibilities increase. Increasing $S$ leads to a reduction in transport costs and the benefits of cultivars with higher straw yield and digestibilities are greatest for low values of $S$.

Another potential benefit of increasing digestibility is the reduction in the number of deliveries. The delivery of feedstock is responsible for a number of environmental and societal impacts such as noise pollution and traffic congestion (Allen et al., 1996). By reducing the number of deliveries these impacts might be lessened, which would benefit planning applications as local opposition to bioenergy plants is based partly on these impacts (Upreti & van der Horst, 2004). Reducing the number of deliveries would reduce traffic around the plant, which could lead to further reductions in transport costs for biomass delivery (Bai et al., 2011).

Determining feedstock demand requires optimising the trade-off between the economy of scale and transport costs. Decreasing transport costs by increasing straw yield would suggest a larger optimum biorefinery size. Argo et al. (2013) suggest that the optimum feedstock demand previously modelled (e.g. Aden et al., 2002) has failed to take into account increased corn stover yields when determining optimum biorefinery capacity, and have, therefore, underestimated optimum biorefinery size. As of yet, no SGB biorefinery size optimisation studies for the UK have been published. If this were to be undertaken, variability in yields and digestibility must be taken into account.

The costs given in the current model are in the middle of the range found in the literature. However, the prices in the literature vary in what the transport costs cover with some not including loading and unloading costs. The costs calculated with this model are higher than those used in Littlewood et al.'s (2013) assessment of SGB production. They found that using current technology, bioethanol production was not economically feasible and bioethanol was not price-competitive with petrol. The higher prices from the current model suggest that achieving this feasibility is more difficult than Littlewood et al.'s economic assessment suggests. The results of the current model suggest that increasing the density of production through a combination of increased straw yield, digestibility and the proportion of land supplying feedstock, might be needed to help achieve price-competitiveness with petrol.

It is important to note that the model presented is based on a number of assumptions that may not hold true in a future biomass supply chain. For example, using average commercial haulage costs to calculate transport costs, as with the current model, might overestimate costs (Rogers & Brammer, 2009). This is because current bioenergy plants have dedicated feedstock haulers and, therefore, might be able to deliver feedstock at lower cost (Allen et al., 1996). However, the percentage differences between hypothetical cultivars still stand.

To achieve these transport cost savings from utilising DPCs requires a significant proportion of the farmers within the feedstock supply area to grow these cultivars. For farmers to grow DPCs the benefits must outweigh the potential trade-offs with other traits such as grain yields. Work is needed to investigate the physiological factors as well as other logistical considerations, such as whether increasing straw yields increases combining and baling costs.

### 5.4. Environmental impacts

In general, environmental burdens calculated for the production of straw in the current LCA were lower than those of Borrion et al. (2012b). However, impact categories varied in how different they were and allocation of emissions between grain and straw had a large impact on the favourability of the results. Because of this the overall EBs for the production of bioethanol varied, demonstrating the importance of the straw production system to the overall EBs.

Following the suggested method of treating straw as a by-product and allocating all emissions occurring prior to the separation of grain and straw to the grain (allocation scenario A1) gave the lowest EBs. This suggested that, overall, EBs from the production of ethanol from wheat straw are lower than calculated by Borrion et al. (2012b) and increase the favourability of the production and use of bioethanol produced from wheat straw compared to the use of petrol.

Treating the straw as a co-product and allocating the EBs between the grain and straw based on mass, price or gross margins lead to higher EBs than the previous scenario where straw was treated as a by-product. Allocation by mass gave higher EBs than allocating by price or gross margin. The results in Borrion et al. (2012b) would be more favourable if economic-based allocation was used.

The results for GHG emissions for the different allocation methods differ from those of Luo et al. (2009) who found lower GHG emissions for allocation by mass. The reason being was that their study took account of biogenic carbon, and increased allocation to the straw meant more $CO_2$ assimilation was allocated to the straw. In the current study, the assimilation of atmospheric $CO_2$ was not considered. However, Luo et al. (2009) found that allocation by mass relative to other allocation systems led to higher emissions for other impact categories, which the current study's results are in agreement with.

Allocation by gross margin gave lower EBs than allocation by price as straw gross margins were a lower percentage of straw price than grain gross margins were of grain price. The use of gross margins in allocation, therefore, makes the production of ethanol from wheat straw more favourable from an EB perspective. The economic component of this project suggests that the importance of straw relative to grain for farmers is less than the prices suggest, whilst for others the importance of straw is more than the price suggests.

Borrion et al. (2012b) found that the production and use of bioethanol-petrol blends led to higher environmental burdens compared to the use of petrol for the acidification, eutrophication, ecotoxicity and water depletion impact categories. Depending on the allocation method used, the results from the current study either increase or decrease the emission of pollutants with acidification, eutrophication, and ecotoxicity impacts relative to the reference system. For all the allocation scenarios excluding the allocation by mass, these emissions are lowered and, although not directly calculated, suggest that these impact categories are favourable compared to the use of petrol. This gives strong support to the use of straw for biofuel production and reduces the issue of trade-offs between the impact categories. However, when allocation by mass was used the emissions were higher and this leads to larger trade-offs between the favourable impact categories and unfavourable impact categories.

Differences in emissions between the hypothetical cultivars were small suggesting that only relatively minor environmental benefits could be achieved by increasing straw yield or digestibility. The exact values varied across scenarios but remained low for all. However, any potential emission savings from increased straw yield would not be seen using the allocation rules of the Renewable Energy Directive (European Commission, 2009); therefore, utilising this would not enable biofuel producers to take account of reductions in emissions. Allocation by mass led to the biggest emission savings from increasing yield, yet these were still small compared to the emissions during the conversion step in the reference system.

The use of fertilisers provides a large proportion of the emissions. These result not just from the production of the fertiliser but also the direct and indirect emissions resulting from its use. The large contribution of fertilisers to overall emissions suggests methods for reducing the need for additional fertiliser would make a significant contribution to lowering emissions. Decreasing N fertiliser use or decreasing direct and indirect emissions resulting from its use are two of the methods most likely to make the production of straw more sustainable. Reductions in N fertiliser could potentially be achieved by growing leguminous cover crops (Tonitto et al., 2006) but it appears that options to reduce N fertiliser use are limited (Barraclough et al., 2010). Another option is to reduce direct and indirect emissions, which could potentially be achieved through the use of nitrification inhibitors (Smith et al., 1997).

Transport had a reasonable contribution to most impact categories. When transport distances from the logistics model were taken into consideration, the differences were relatively minor. It is possible that other studies have underestimated transport distances, possibly through only accounting for one-way journeys. However, the current work suggests this would only have a minor impact on overall emissions. Based on the logistics work it is likely feedstock sourcing distances will be limited by costs rather than considerations regarding transport emissions.

### 5.5. Survey

The majority of farmers use three or more information sources when choosing which cultivars to grow, with the number of sources higher for larger farms. AHDB RLs are one of the most widely used information sources; 91% of respondents willing to manage for wheat straw yields rated them as important or very important, which suggests that, should the price of straw increase and managing for increased straw yield becomes more important, providing information on straw yields in these RLs would make this information available to almost all farmers.

A comparison of data from the current survey to those of Glithero et al. (2013a) found more straw was chopped and incorporated in 2012 than 2010 in all regions apart from the East of England where the same amount of straw was incorporated. There are a number of reasons why this may be the case; firstly, straw yields were low in 2010, which meant more hectares would have needed to be harvested to meet demand. Secondly, the wet weather in 2012 discouraged some farmers from baling their straw. It is unclear why the rates are the same for the East of England but could be related to the lower straw demand in this region.

There was a positive correlation between the size of the farm and the amount of straw chopped and incorporated, supporting unpublished data from the survey conducted by Glithero et al. (2013a). It is unclear why larger farms chopped a greater proportion of their straw. Glithero et al. asked respondents the reasons why they chopped straw; using unpublished data from that study offers some insight into the supply of straw. The lower supply in larger farms did not appear to result from a lack of a market as very few respondents gave this as a barrier to supply. Smaller farms were more likely to cite lack of equipment, concerns about contractors and perceived benefits of incorporation and soil compaction concerns from baling as reasons why they did not bale all of their straw. A similar proportion of farms from small, medium and large farmers cited timeliness concerns as a reason why they did not bale all of their straw. However, although this shows reasons why farmers are not baling all of their straw it does not show what proportion of straw is being chopped because of those concerns. Although timeliness concerns were even across farm sizes, it could be that these concerns led to a greater proportion of straw being chopped on larger farms than smaller farms.

For both studies the largest surplus was in the East of England, which suggests this would be good location for a bioenergy plant. In fact, the majority of the current and planned capacity for straw-burning bioenergy is in the East Midlands and East of England. However, although not significant, there was a strong trend for farmers in the East of England to be less willing to supply straw should it reach a price of £100 $t^{-1}$. This might mean less straw is available than expected in this region.

The average price at which farmers would be willing to start managing their wheat for straw yields is approximately £90 $t^{-1}$, which is £40 above the average price farmers were willing to sell their straw identified by Glithero et al. (2013b). However, there was considerable variation in the price farmers were willing to manage their straw for. An increase in the price of straw might also influence mixed farms to manage their wheat for increased yields so they reduce their costs from having to buy straw in.

The clear preference for farmers was to grow cultivars with greater straw yields. There were many concerns about increased lodging risk from higher straw yields and this might be reflected in a lower selection rate for not using PGRs. The field experiments found chlormequat application does not necessarily lower straw yields so the increased risk of lodging might not be offset by an increased straw yield. Although the responses suggest that some farmers would be willing to use management practices to increase straw yield, either to sell or use on their own farms, there is little work investigating how to increase straw yields, and the extent of trade-offs with grain yield and quality that might result. It is also unclear how increased straw yields will influence collection costs.

It has been shown in other studies that a significant proportion of farmers are unwilling to sell their straw (e.g. Glithero et al., 2013b). In this study, even at a guaranteed price of £100 $t^{-1}$, 21% of farmers stated they were unwilling to sell any extra straw. In fact, 7% of respondents incorporated all their straw and were unwilling to sell any of it. ADAS (2008), in estimating straw supply, suggested only 2% of farmers would be unwilling to supply straw at £60 $t^{-1}$. This data suggests that ADAS' result is overestimated. Littlewood et al. (2013) found that the price of bioethanol is very price sensitive to wheat straw prices, so this suggests that straw would be prohibitively expensive at £100 $t^{-1}$. Therefore, this survey strongly suggests that even with increased straw prices, a large proportion of straw will be unavailable for use in the biofuel sector and means that some current estimates of straw availability in England for biofuel production are too high (e.g. Scarlat et al., 2010).

There were no significant differences between the groups in their willingness to supply straw at a price of £100 $t^{-1}$. Respondents who were unwilling to sell extra straw placed more importance on land stewardship, family objectives and quality of life as farming objectives. There was a strong trend for placing importance on maintaining the environment. Land stewardship and family objectives suggest that those respondents have a long-term perspective for their farms and it is possible that they see the long-term viability of the soil requires a limit to the amount of straw removed.

Although there have been many estimates of straw availability, very few studies have considered the impact of large-scale demand from biorefineries on local supply. Even if, on a national scale, there is sufficient residue available for a biofuel sector, this could still increase the price of straw for livestock farmers and other straw users. This is because distribution is important. As transport costs for straw are high straw needs to be sourced from nearby. Taken with the economy-of-scale aspects, where the optimum size of a biorefinery is likely to have a large feedstock requirement, this suggests that areas around biorefineries will be in competition with other users of wheat straw, forcing people to source feedstock from further away, adding extra costs. This could push prices up for livestock farmers even if, on the national scale, there is enough straw available.

## 5.6. Conclusions and recommendations

### 5.6.1. Dual-purpose cultivars

Although differences in traits were found between the cultivars the current project did not find an outstanding candidate for use as a DPC. However, only a limited number of cultivars were assessed and work by other authors does suggest that modern cultivars can significantly differ in terms of straw yield so assessment of a wider range of cultivars might identify suitable candidates. However, it appears that the range of values is likely to be low. Although older cultivars produce greater straw yields (Austin et al., 1980; Roy, 2014), they are unlikely to be considered for use as DPC because of low grain yields and high lodging susceptibility.

Grafton appeared to be a good candidate due to it having high grain yield, and the highest digestibility and lodging resistance of the three cultivars. The drawback of this cultivar is that it had the lowest straw yield (when considering a 10 cm cutter bar height). Its suitability as a DPC will, therefore, depend on the relative value of grain and straw, the risk of lodging events and whether a premium is paid for higher digestibility material. Although Grafton could be considered the most appropriate cultivar for use as a DPC, another aspect that must be considered is the grain quality and this adds another layer of complexity in selecting a cultivar. Grafton is a feed wheat whereas both Cordiale and Xi19 are milling wheats. This means that Cordiale and Xi19's grain would get a premium price but Grafton's would not. Whether a farmer grows a milling wheat or a feed wheat depends on their location as well as their personal preferences. A lot of the areas where a future biofuel plant could be located are areas where both feed and milling wheats are grown so DPCs could take the form of either milling-quality or feed wheats. However, it could be argued milling wheats tend to require greater management in terms of nutrients, pest control and lodging control to gain the quality thresholds required for the premiums and, therefore, these farmers would be less interested in managing for extra straw. Because of this, it may be that the most appropriate type of wheat for a DPC would be a feed wheat.

At the moment there is significant uncertainty about the technologies that would be used for SGB production, with particular reference to how differing digestibility will affect the process. This means that it is unclear whether differences in this trait between cultivars would be seen at the industrial-scale, and, therefore, whether that aspect of DPCs is worth developing. Of the studies considering wheat straw, only Lindedam et al. (2010) undertook pilot-scale experiments to assess digestibility and, although they found differences between cultivars, the overall range was small. Another complication arises from the different types of pretreatment and enzymes that can be used in processing and which, if any, will be used at commercial-scale. This is of particular relevance due to the varying response of cultivars to hydrothermal treatment (Lindedam et al. 2010), with differences between cultivars being more pronounced/only found under certain conditions.

Even if differences in digestibility translate to changes at the industrial-scale, constraints may limit uptake or preference of set cultivars by biofuel producers. These include time and cost constraints associated with testing the digestibility of straw plus the strong influence of environmental conditions on straw traits such as digestibility. This means that knowledge of the cultivar may be an incomplete indication of the digestibility. Bruun et al. (2010) demonstrated the use of near-infrared spectroscopy to predict digestibility, and Lindedam et al. (2014) demonstrated the use of high throughput screening methods to assess digestibility, which could make testing at the biorefinery gate possible. Processors will only take account of digestibility if it makes financial sense; the additional ethanol yield or reduction in processing costs from using more digestible material would need to outweigh the costs of testing material and paying farmers a premium for this material. However, incentivising higher digestibility straw requires that farmers are able to select cultivars and management practices that produce high digestibility; thus requiring infrastructure to make this knowledge available.

Based on the current biorefineries producing bioethanol from wheat grain, it is unlikely that producers will differentiate feedstock based on digestibility when the industry develops. FGB yield varies between wheat cultivars and there is a negative relationship between protein content and starch content in wheat grain, allowing an estimation of potential bioethanol yield (Smith et al., 2006). However, there is currently a flat rate paid per tonne of grain, regardless of potential bioethanol yield (pers. comm. Nick Oakhill, Glencore).

Other processes or treatments may also be undertaken which improve the processing of the straw. For example, allowing the straw to lie on the ground before harvest allows rain showers to wash out substances that negatively impact on the furnaces. Although this practice is beneficial to straw-fired power stations, in the Swedish straw bioenergy sector, farmers are not paid more for straw that has had these substances washed out (Skøtt, 2011).

An aim of these field experiments was to analyse trade-offs between the key traits. The data suggested a link between the digestibility of the plant material and the material strength of the lower internodes. Grafton had the lowest material strength of the lower internodes and also the greatest digestibility, which is the opposite of Cordiale, and suggests that the weaker the stem material is, the easier the material is to digest. It is also unclear how the material characteristics of the lower two internodes, which only make up a small amount of the overall stem, is related to the material strength of the rest of the stem.

Lodging is determined not only by material strength but also by the HCG. The relationships between height and digestibility found in other studies were not found in the current study suggesting that there is not a height-related lodging risk with differences in digestibility. Lodging effects on straw quality and yield appear not to have been discussed in the literature with regards to biofuel production. It can be surmised that if the straw is leaning close to the ground then a combine harvester will take in less straw and, therefore, baled straw yields will be lower. This straw might also be damper, which could potentially lead to increased dry matter losses during storage and a lower price for not achieving the low moisture requirements. No work has considered how the ethanol yield potential of straw might be influenced by lodging.

The investigation considered whether there were trade-offs between the key traits but due to the limited number of cultivars considered it was difficult to determine the relationships between these traits. The literature strongly suggested that there are positive correlations between straw height and straw yield, and straw height and lodging risk. From this it can be assumed that lodging risk increases with straw yield. The results of the field experiment gave some support to this.
The literature also suggested a trade-off between good digestibility and the breaking strength of the lower stem. The current study did find the least digestible cultivar had the greatest material strength of the lower internodes. However, this correlation is not seen in Roy (2014) so there is not strong support for this relationship.

The data could be seen to suggest that there is a negative relationship between grain and straw due to the highest straw-yielding cultivar having the lowest grain yield. However, as discussed above, the grain yields for Xi19 are lower than the average values from the AHDB RL data. In other studies the relationship between grain yield and straw yield varies depending on which cultivars are being considered. For example, in modern cultivars, there tends to be a positive relationship as greater productivity resulting from beneficial growing conditions increases both straw and grain yields. If older cultivars are included then a negative relationship is seen as older cultivars have greater straw yields and lower grain yields.

To complement selection of a DPC, management practices that might optimise the traits of a DPC were investigated. Chlormequat was found, as expected, to reduce lodging risk. However, the influence of chlormequat on straw yields was not as clear. It appears that straw yields are reduced with the application of chlormequat, but only by a small amount and only when the lower 15 cm of stem was excluded. There is limited research investigating the influence of chlormequat on straw yield but the few studies that have considered it appear to mask any potentially differences in straw yields by collecting all straw rather than attempting to replicate the collection of straw by a baler after combining. The effect of chlormequat on grain yield was inconsistent but it did appear to increase straw digestibility. Therefore, using chlormequat can reduce lodging risk and increase digestibility, but this could be at the expense of reduced straw yield, depending on the combine cutter bar height. Quantifying these trade-offs to determine whether chlormequat should be used is not possible with the current data. Although this work has shown that chlormequat and cultivar can have an influence on the digestibility of wheat straw, the actual importance to biofuel production is unclear. These assays are optimised to show differences between cultivars and it is not possible to determine how chlormequat would influence sugar yields when the straw is being processed at an industrial scale.

Drawing conclusions from the N treatments is difficult as it is not clear when the additional N was available to the plants and whether there was already more N available due to mineralisation from high rainfall. The data suggests that N did not provide benefits in terms of grain or harvestable straw yields, digestibility or lodging resistance, the study suggests that additional N application above the recommended amounts would not benefit farmers. Further work is needed to determine whether, under different weather conditions, additional N provides benefits. The higher yields, digestibility or lodging resistance would have to be large enough to warrant the extra expenditure on N fertiliser and the problems of managing increased nitrate emissions from the additional N.

From the farmer survey lodging resistance was given as an important or very important trait by 90% of respondents. A number of respondents expressed concerns about increased lodging risk resulting from higher straw yields. This suggests that if there are trade-offs between lodging and straw yield then farmers are likely to favour good lodging resistance at the expense of a higher straw yield.

The project only considered a limited number of traits and other trade-offs could exist. For example, there could be a relationship between digestibility and susceptibility to pests and disease. It has been suggested that there is an upper limit to improvements in digestibility because altering the cell wall components could result in weakening, leading to reduced integrity (Pauly & Keegstra, 2008). This could leave the plant more susceptible to pathogens or attacks by pests (Li et al., 2008). However, the digestibility of different cultivars has not been compared to disease susceptibility and risk of damage from pests.

The selection or development of a DPC would depend on the potential benefits of growing this over a cultivar with optimised grain yield. The economic analysis did suggest a small increase in gross margins for farmers from increasing straw yield and digestibility. However, the model did not take account of potential risks from higher straw yield in years when climatic conditions, or other factors, prevent baling of straw and necessitate the chopping and incorporation of straw, the costs of which would be greater for higher straw yields. The additional gross margins are unlikely, on their own, to encourage many farmers to grow DPCs, in particular risk-averse farmers. With an increase in straw price, the higher gross margins might be enough to encourage farmers to increase straw yields.

The logistic model suggested some potential savings for higher straw yields and digestibilities in terms of haulage costs. This is assuming that a company is delivering the entire straw demand so the benefits will not be noticeable if farmers are delivering the straw themselves. It also assumes that all farmers supplying straw to the biorefinery are growing DPCs. If these assumptions are met, and a cost saving is achieved, then the cost savings could be passed on to farmers to encourage their uptake of DPCs.

Life cycle assessment has demonstrated that there are environmental benefits from increasing straw yield and digestibility. However, these are small and it is unclear whether they could lead to an added benefit to biofuel producers (e.g. GHG emission savings relative to the use of petrol must exceed a minimum level but current legislation does not reward biofuel producers for emissions savings beyond this). Currently, none of the environmental burdens of the production of wheat are allocated to the straw for biofuel production (European Commission, 2009). However, the problem with this is that emissions savings during the straw production stage are not taken into account, and would not provide any benefits to biofuel producers. If these were to be included, as well as a requirement to accurately take account of changes to soil organic carbon from the removal of crop residue, then the benefits of increased straw yield would become more apparent.

From the survey it is apparent that some farmers would be unwilling to supply straw meaning that some of the available resource will not be accessible to biofuel producers. This seems strongest in the East of England, where there is the greatest amount of straw that is chopped and incorporated. Further research is needed to identify why there is this opposition to the sale of straw in this region and determine whether it is possible to encourage greater willingness to supply straw.
From the survey it was apparent that some farmers would be willing to grow DPCs if straw prices were to increase. However, the average management price cited to incentivise management change was £90.86 $t^{-1}$, which is approximately twice as much as farmers are currently receiving for their straw for bioenergy production. One of the main reasons for the high price appeared to be because of worries about compromising grain yield and increasing lodging risk. Unless the price of straw increases significantly it is unlikely that farmers will be willing to grow DPCs.

### 5.6.2. Recommendations

***Growers***

Regardless of the development of biofuels, there is likely to be an increase in demand for wheat straw from straw-burning power plants and, therefore, increasing straw yields might become desirable to farmers, both for those wishing to supply straw to this sector and those requiring straw for livestock. Due to uncertainty about the importance of digestibility as a quality parameter in biofuel production and whether a premium would be paid for higher digestibility straw, the straw digestibility should not be a major determining factor in cultivar choice for farmers. With the small range of wheat straw yields it is likely to be difficult to identify a cultivar that gives consistently high straw yields from the currently grown cultivars. If a farmer wishes to increase straw yield then a better option would be to grow triticale. The higher straw yields as well as other key benefits (e.g. greater hardiness; McGoverin et al., 2011) strongly support its use for a DPC.

Should a farmer wish to supply straw, our data showed chlormequat to have limited impact on straw yields and hence the benefits of reduced lodging are likely to outweigh any potential reduction in straw yield. The influence of chlormequat on straw yield was only apparent at a simulated 15 cm combine cutter height, so for increased straw yields it would be more appropriate to lower the cutter height rather than reduce chlormequat use. The N fertiliser recommendations with respect to straw yields are not as clear cut, but it is likely that additional N would provide little benefit for straw yields but would increase variable costs as well as increase direct emissions (e.g. $N_2O$ and nitrate). Therefore, N fertiliser rates should continue to follow those recommended by RB209 (2010).

***Crop breeders***

Instead of selection of an existing cultivar for use as a DPC, a cultivar with the attributes of a DPC could be developed via breeding. The costs and time taken to breed new cultivars is high so there would have to be strong evidence that these traits could be successfully developed, and that there will be a secure market for these new cultivars. Jensen et al. (2011) and Lindedam et al. (2010) suggest there is a strong heritability of digestibility, which opens up the possibility of selecting for this trait. However, as it is unclear whether higher digestibility will be a desirable trait, there is little incentive in developing these cultivars. Straw yield might be a more beneficial trait if it can be achieved without significantly reducing grain yield potential. If the price of straw were to increase then there is likely to be a market for these cultivars. Breeding a cultivar with higher straw yield without compromising grain yield and lodging resistance requires an increase in overall productivity. As we are currently reaching the theoretical limit for any increases in harvest index (Shearman et al., 2005), any future breeding attempts to increase grain yield might concurrently bring about increases in straw yield. Thus, unless specific traits relating to processing of the straw are required, there may be no incentive to have a designated breeding programme to develop DPCs for the biofuel industry.

***Biofuel producers***

Due to a large proportion of farmers being unwilling to supply straw there is likely to be less straw available for the bioenergy sector than previously estimated. This means that large biorefineries are not feasible and biofuel producers should aim for smaller-scale production. Increasing straw yield, and/or the proportion of land supplying straw, decreases transport costs and negative environmental externalities so efforts should be made to achieve this. Concerns about compaction and timeliness are often cited as reasons for farmers not supplying straw. This suggests that a dedicated straw-collecting company, with new technologies to reduce soil compaction, and speed up the collection of straw to prevent delays to other farm operations, may be required.

***AHDB Cereals & Oilseeds***

The work suggests that increasing straw yields might be desirable to farmers. As mentioned in the previous section, this would necessitate more information being made available to farmers. It was suggested that, of the three cultivars assessed in the final field experiment, Grafton would be the best suited for use as a DPC. However, as it is a feed wheat its overall value is likely to be lower than Xi19 and Cordiale. Further work is needed to identify the most appropriate cultivars for use as DPCs. The farmer survey suggests that the Recommended Lists produced by AHDBare widely used in the farming community for assisting the selection of wheat cultivars and, therefore, these are the ideal medium for providing data on straw yields. Based on the low variability in straw yields of modern cultivars this could be based on a two-level rating (e.g. low and high).

***Policy makers***

Overestimation of straw availability for biofuel production has important implications for policy makers. Better estimates of straw availability are required to inform decisions about the direction of renewable energy policy. Work is also needed to determine how straw use for bioenergy will compete with other users of straw. Most importantly farmers should be treated as stakeholders when investigating the best options for bioenergy projects.

The current study has recommended ways in which to increase farmer participation in supplying straw which might potentially increase straw availability. This also needs to be taken into account in future estimates of straw availability. Such knowledge can be used to encourage exploration of the use of other feedstocks (e.g. oilseed rape straw) or potentially more appropriate ways of utilising these crop residues (e.g. small-capacity combined heat and power stations). More detailed understanding of the feasibility of such systems could also be used to encourage further investment in the sector.

LCA work has demonstrated that reducing environmental burdens can be achieved through decisions taken at the farm level. However, McKone et al. (2011) highlight the difficulty of using LCA to inform policy and influence decision making at the farm level because each individual farmer is a decision maker. As each farm is different, providing guidance for the reduction of environmental burdens is difficult. To maximise the environmental benefits of using straw for bioenergy generation, policy makers should work with agricultural organisations to produce guidelines for sustainable straw supply.

### 5.6.3. Final message

This project has highlighted large gaps in knowledge that are critical for expansion of SGB production in the UK. It is clear that published studies are overestimating the quantity of straw available to biorefineries and a lot more infrastructure, both in terms of information and collection methods, is required to accurately predict the feasibility of such systems. Furthermore, farmer participation will be critical for any future development; something that has not had sufficient attention.

Based on the literature and the results of this current study it is the authors' opinion that straw has an important role in the future of renewable energy production in the UK but not for producing biofuels. Burning straw in combined heat and power facilities appears to be the most appropriate use of straw as much higher efficiencies can be achieved this way. As highlighted by Gnansounou (2010), the development of biofuels prolongs the use of internal-combustion engines, which are inefficient ways of utilising fuels. Instead, research should focus on the development of more efficient transportation methods, such as electric cars, the electricity of which could be generated from burning straw. LCA work has shown this could be a better use of straw (e.g. Campbell et al., 2009). Whichever technology or mix of technologies are used it is hoped this investigation has provided information that will benefit the future of bioenergy production in the UK.

## 6. References

**ABC (2013)** *The Agricultural Budgeting and Costing Book*. No. 77. Agro Business Consultants Ltd.

**Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A. and Lukas, J. (2002)** *Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover*. National Renewable Energy Laboratory, Colorado. NREL/TP-510-32438.

**ADAS (2008)** *Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities.* NNFCC project 08-004.

**AEC (2012)** *Cellulosic biofuels*. Industry Progress report 2012-2013.

**Allen, J., Browne, M., Hunter, A., Boyd, J. and Palmer, H. (1996)** Logistics management and costs of biomass fuel supply. *International Journal of Physical Distribution & Logistics Management* **28**(6): 463-77

**Anon (2003)** *An assessment of the renewable energy resource potential of dry agricultural residues in Ireland*. A report prepared for Sustainable Energy Ireland by RPS MCOS. Dublin, Ireland.

**Anon (2010)** *'Hay and straw prices could be 40% higher this season'*. Website accessed 13th August 2014: <http://www.fwi.co.uk/articles/08/07/2010/122151/39hay-and-straw-prices-could-be-40-higher-this-season39.htm>

**Anon (2012)** *Managing sustainable straw supply for renewable energy generation*. Website accessed 22nd November 2012:

<http://www.farmersguardian.com/home/machinery/machinery-features/managing-sustainable-straw-supply-for-renewable-energy-generation/48317.article>

**Anon (2013a)** *AFBI cereal recommended lists.* Website accessed 2nd August 2014 <http://eservices.afbini.gov.uk/recommendedvarieties/cereals/default.aspx>

**Anon (2013b)** *Weather statistics*. Website accessed 19th August 2014: <http://www.metoffice.gov.uk/news/releases/archive/2013/2012-weather-statistics>

**Argo, A.M., Tan, E.C.D., Inman, D., Langholtz, M.H., Eaton, L.M., Jacobson, J.J., Wright, C.T., Muth Jr., D.J., Wu, M.M., Chiu, Y.-W. and Graham, R.L. (2013)** Investigation of biochemical biorefinery sizing and environmental sustainability impacts for conventional bale system and advanced uniform biomass logistics designs. *Biofuels, Bioproducts and Biorefining* **7**(3): 282-302

**Austin, R.B., Bingham, J., Blackwell, R.D., Evans, L.T., Ford, M.A., Morgan, C.L. and Taylor, M. (1980)** Genetic improvements in winter wheat yields since 1900 and associated physiological changes. *Journal of Agricultural Science* **94**: 675-689

**Baker, E.A. and Hunt, G.M. (1985)** Factors affecting the uptake of chlormequat into cereal leaves. *Annals of Applied Biology* **106**(3): 579-590

**Baker, C.J., Berry, P.M., Spink, J.H., Sylvester-Bradley, R., Griffen, J.M., Scott, R.K. and Clare, R.W. (1998)** A method for the assessment of the risk of wheat lodging. *Journal of Theoretical Biology* **194**: 587-603

**Bai, Y., Hwang, T., Kang, S., Ouyang, Y. (2011)** Biofuel refinery location and supply chain planning under traffic congestion. *Transportation Research Part B* **45**: 162-175

**Banham, G. (2011)** *Chop or bale? Our cost/benefit analysis explores the answers*. Farmers Weekly, 25 July 2011.

**Barraclough, P.A., Howarth, J.R., Jones, J., Lopez-Bellido, R., Parmar, S., Shepherd, C.E. and Hawkesford, M.J. (2010)** Nitrogen efficiency of wheat: Genotypic and environmental variation and prospects for improvement. *European Journal of Agronomy* **33**: 1-11

**Berry, P.M., Griffin, J.M., Sylvester-Bradley, R., Scott, R.K., Spink, J.H., Baker, C.J. and Clare, R.W. (2000)** Controlling plant form through husbandry to minimise lodging in wheat. *Field Crops Research* **67**: 59-81

**Berry, P.M., Spink, J.H., Gay, A.P. and Craigon, J. (2003a)** A comparison of root and stem lodging risks among winter wheat cultivars. *Journal of Agricultural Science* **141**: 191-202

**Berry, P.M., Spink, J., Sterling, M. and Pickett, A.A. (2003b)** Methods for rapidly measuring the lodging resistance of wheat cultivars. *Journal of Agronomy and Crop Science* **189**: 390-401

**Berry, P.M., Sterling, M., Spink, J.H., Baker, C.J., Sylvester-Bradley, R., Mooney, S., Tams, A. and Ennos, A.R. (2004)** Understanding and reducing lodging in cereals. *Advances in Agronomy* **84**: 217-271

**Berry, P.M., Sylvester-Bradley, R. and Berry, S. (2007)** Ideotype design for lodging-resistant wheat. *Euphytica* **154**: 165-179

**von Blottnitz, H. and Curran, M.A. (2007)** A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner Production* **15**: 607-619

**Borrion, A.L., McManus, M.C. and Hammond, G.P. (2012a)** Environmental life cycle assessment of lignocellulosic conversion to ethanol: a review. *Renewable and Sustainable Energy Reviews* **16**: 4,638-4,650

**Borrion, A.L., McManus, M.C. and Hammond, G.P. (2012b)** Environmental life cycle assessment of bioethanol production from wheat straw. *Biomass and Bioenergy* **47**: 9-19

**Boscoe, F.P., Henry, K.A. and Zdeb, M.S. (2012)** A nationwide comparison of driving distance versus straight-line distance to hospitals. *The Professional Geographer* **64**(2): 188-196

**Bruun, S., Jensen, J.W., Magid, J., Lindedam, J. and Engelsen, S.B. (2010)** Prediction of the degradability and ash content of wheat straw from different cultivars using near infrared spectroscopy. *Industrial Crops and Products* **31**: 321-326

**Campbell, J.E., Lobell, D.B. and Field, C.B. (2009)** Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science* **324**: 1,055-1,057

**Capper, B.S. (1988)** Genetic-variation in the feeding value of cereal straw. *Animal Feed Science and Technology* **21**: 127-40

**Caputo, A.C., Palumbo, M., Pelagagge, P.M. and Scacchia, F. (2005)** Economics of biomass energy utilization in combustion and gasification plants:effects of logistic variables. *Biomass and Bioenergy* **28**: 35-51

**Carriquiry , M.A., Du, X. Timilsina, G.R. (2011)** Second generation biofuels: economics and policies. *Energy Policy* **39**: 4,222-4,234

**Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch, S. (2009)** Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling* **53**: 434–447

**Cherubini, F. and Strømman, A.H. (2011)** Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology* **102**: 437–451

**Cherubini, F. and Ulgiati, S. (2010)** Crop residues as raw materials for biorefinery systems – a LCA case study. *Applied Energy* **87**: 47-57

**Copeland, J. and Turley, D. (2008)** *National and regional supply/demand balance for agricultural straw in Great Britain.* Report prepared for The National Non-Food Crops Centre.

**Crook, M.J. and Ennos, A.R. (1995)** The effect of nitrogen and growth regulators on stem and root characteristics associated with lodging in two cultivars of winter wheat. *Journal of Experimental Botany* **46**(289): 931-938

**Defra (2014)** *Hay & Straw, England & Wales average prices*. Defra commodity prices. Data provided by British Hay & Straw Merchants' Association. Website accessed 15th May 2014: <https://www.gov.uk/government/statistical-data-sets/commodity-prices>

**Demirbas, A. (2008)** Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management* **49**: 2,106-2,116

**DFF (2013)** *RHA cost tables 2013*. Prepared by DFF International LTD.

**Donaldson, E., Schillinger, W.F. and Dofing, S.M. (2001)** Straw production and grain yield relationships in winter wheat. *Crop Science* **41**: 100-106

**Eco2 UK (2014)** *Sleaford renewable energy plant*. Website accessed 2nd August 2014: <http://www.eco2uk.com/en/our_projects/project_detail.asp?project_id=9>

**Engel, R.E., Long, D.S. and Carlson, G.R. (2003)** Predicting straw yield of hard red spring wheat. *Agronomy Journal* **95**: 1,454-1,460

**European Commission (2009)** *Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.* L140/16-62: Official Journal of the European Union.

**European Commission (2013)** *Clean Power for Transport: A European alternative fuels strategy*. Communication from the Commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the Regions

**Gallagher, P., Dikeman, M., Fritz, J., Wailes, E., Gauther, W. and Shapouri, H. (2003)** *Biomass from crop residues: cost and supply estimates*. USDA, Office of the Chief Economist, Office of Energy Policy and New Uses; February 2003. 30 p. Agricultural Economic Report No.:819.

**Garthwaite, D.G., Barker, I., Parrish, G., Smith, L., Chippindale, C. and Pietravalle, S. (2011)** *Pesticide usage survey report 235: arable crops in the United Kingdom 2010*. Agricultural Survey Team, Food & Environment Research Agency

**Glithero, N.J., Wilson, P. and Ramsden, S.J. (2013a)** Straw use and availability for second generation biofuels in England. *Biomass and Bioenergy* **55**: 311-321

**Glithero, N.J., Ramsden, S.J. and Wilson, P. (2013b)** Barriers and incentives to the production of bioethanol from cereal straw: a farm business perspective. *Energy Policy* **59**: 161-171

**Gnansounou, E. (2010)** Production and use of lignocellulosic bioethanol in Europe: Current situation and perspectives. *Bioresource Technology* **101**: 4,842-4,850

**Green, C.F., Dawkins, T.C.K. and Hunter, B. (1985)** Influence of foliar applied chlormequat on radiation attenuation by winter barley canopies. *The Journal of Agricultural Science* **105**(1): 213-216

**Habib, G., Shah, S.B.A. and Inayat, K. (1995)** Genetic variation in morphological characteristics, chemical composition and in vitro digestibility of straw from different wheat cultivars. *Animal Feed Science Technology* **55**: 263-274

**AHDB (2009)** *Assessing the nutrient content of straw*. Information sheet 05, Spring 2009.

**AHDB (2013)** *Planting survey results 2013*. Website accessed 30th June 2014: <www.hgca.com/media/5314/Planting_survey_results_2013.pdf>

**Huang, H.-J., Ramaswamya, S., Al-Dajania, W., Tschirnera, U. and Cairncross, R.A. (2009)** Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass and Bioenergy* **33**: 234-246

**IPCC (2007)** *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA..

**IPNI (2008)** *Average nutrient removal rates for crops in the Northcentral Region*. Plant Nutrition TODAY, No. 4, from the International Plant Nutrition Institute.

**Jensen, J.W., Magid, J., Hansen-Møller, J., Andersen, S.B. and Bruun, S. (2011)** Genetic variation in degradability of wheat straw and potential for improvement through plant breeding. *Biomass and Bioenergy* **35**: 1,114-1,120

**Kaylen, M., Van Dyne, D.L., Choi, Y.-S. and Blase, M. (2000)** Economic feasibility of producing ethanol from lignocellulosic feedstocks. *Bioresource Technology* **72**: 19-32

**Kernan, J.A., Coxworth, E.C., Crowle, W.L. and Spurr, D.T. (1984)** The nutritional value of crop residue components from several wheat cultivars grown at different fertilizer levels. *Animal Feed Science Technology* **11**: 301-311

**Kim, S. and Dale, B.E. (2011)** Indirect land use change for biofuels: testing predictions and improving analytical methodologies. *Biomass and Bioenergy* **35**(7): 3,235-3,240

**Knapp, J.S., Parton, J.H. and Walton, N.I. (1983)** Enzymic saccharification of wheat straw - differences in the degradability of straw derived from different cultivars of winter wheat. *Journal of the Science of Food and Agriculture* **34**: 433-439

**Larsen, S.U., Bruun, S. and Lindedam, J. (2012)** Straw yield and saccharification potential for ethanol in cereal species and wheat cultivars. *Biomass and Bioenergy* **45**: 239-250

**Leboreiro, J. and Hilaly, A.K. (2011)** Biomass transportation model and optimum plant size for the production of ethanol. *Bioresource Technology* **102**: 2,712-2,723

**de Leon, N. and Coors, J.G. (2008)** *Genetic Improvement of Corn for Lignocellulosic Feedstock Production.* In: Genetic Improvement of B`ioenergy Crops. [Ed. Wilfred Vermerris.] Springer, New York, USA.

**Levelton Engineering Ltd. (2000)** *Assessment of net emissions of greenhouse gases from ethanol-blended gasolines in Canada: lignocellulosic feedstocks*. R-2000-2, Levelton Engineering Ltd., Richmond, Canada.

**Li, X., Weng, J.-K. and Chapple, C. (2008)** Improvement of biomass through lignin modification. *The Plant Journal* **54**: 569-581

**Lindedam, J., Andersen, S.B., DeMartini, J., Bruun, S., Jørgensen, H., Felby, C., Magid, J., Yang, B. and Wyman, C.E. (2012)** Cultivar variation and selection potential relevant to the production of cellulosic ethanol from wheat straw. *Biomass and Bioenergy* **37**: 221-228

**Lindedam, J., Bruun, S., Jørgensen, H., Felby, C., and Magid, J. (2010)** Cellulosic ethanol: interactions between cultivar and enzyme loading in wheat straw processing. *Biotechnology for Biofuels* **3**(25)

**Littlewood, J., Murphy, R.J. and Wang, L. (2013)** Importance of policy support and feedstock prices on economic feasibility of bioethanol production from wheat straw in the UK. *Renewable and Sustainable Energy Reviews* **17**: 291-300

**Luo, L., van der Voet, E., Huppes, G. and Udo de Haes, H.A. (2009)** Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol. *International Journal of Life Cycle Assessment* **14**: 529–539

**Mabee, W.E., Fraser, E.D.G., Mcfarlane, P.N. and Saddler, J.N. (2006)** Canadian biomass reserves for biorefining. *Applied Biochemistry and Biotechnology* **129–132**: 22-40

**MAFRD (2014)** *Guidelines for estimating wheat straw biomass production costs 2014: High crop residue zone in Manitoba*. Manitoba Agriculture, Food and Rural Development Growing Opportunities Office. ESR-016086.

**McGoverin, C.M., Snyders, F., Muller, N., Botes, W., Fox, G. and Manley, M. (2011)** A review of triticale uses and the effect of growth environment on grain quality. *Journal of the Science of Food and Agriculture* **91**: 1,155-1,165

**McKendry, P. (2002)** Energy production from biomass (part 1): overview of biomass. *Bioresource Technology* **83**: 37-46

**McKone et al. (2011)** Grand challenges for life-cycle assessment of biofuels. *Environmental Science and Technology* **45**: 1,751-1,756

**Menichetti, E. and Otto, M. (2009)** *Energy balance and greenhouse gas emissions of biofuels from a life-cycle perspective*. Pages 81-109 in R.W. Howarth and S. Bringezu (eds) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA.

**Miao, Z., Shastri, Y., Grift, T.E., Hansen, A.C and Ting, K.C. (2012)** Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modelling. *Biofuels, Bioproducts and Biorefining* **6**: 351-362

**Midwood, J. and Birbeck, P. (n.d.)** *Managing heavy stubble loads and crop residue.* Chapter 1, Managing stubble. Våderstad Pty Ltd.

**Mitchell, D. (2008)** *A Note on Rising Food Prices*. Policy research working paper 4682. The World Bank, Development Prospects Group.

**NAAC (2012)** *NAAC contractor charges 2012-13.* Mid prices quoted from the National Association of Agricultural Contractors and compiled by Farmers Weekly. Website accessed 21st October 2013: <http://www.fwi.co.uk/articles/01/08/2012/134237/naac-contractor-charges-2012-13.htm>

**Naylor, R.E.L. (1989)** Effects of the plant growth regulator chlormequat on plant form and yield of triticale. *Annals of Applied Biology* **114**(3): 533-544

**Newman, R. (2003)** *A trial burn of rape straw and whole crops harvested for energy use to assess efficiency implications*. New & Renewable Energy Program, Department of Trade & Industry, England. B/U1/00768/00/00 URN 03/1569.

**Nilsson, D. (2000)** Dynamic simulation of straw harvesting systems: influence of climatic, geographical and biological factors on performance and costs. *Journal of Agricultural Engineering Research* **76**: 27-36

**Nix, J. (2013)** *John Nix Farm Management Pocketbook*. 44th edition. Agro Business Consultants Ltd.

**Overend, R.P. (1982)** The average haul distance and transportation work factors for biomass delivered to a central plant. *Biomass* **2**: 75-79

**Pauly, M. and Keegstra, K. (2008)** Cell-wall carbohydrates and their modification as a resource for biofuels. *The Plant Journal* **54**: 559-568

**Phitsuwan, P., Sakka, K. and Ratanakhanokchai, K. (2013)** Improvement of lignocellulosic biomass *in planta*: a review of feedstocks, biomass recalcitrance, and strategic manipulation of ideal plants designed for ethanol production and processability. *Biomass and Bioenergy* **58**: 390-405

**Rademacher, W. (2000)** Growth retardants: effects on gibberellin biosynthesis and other metabolic pathways. *Annual Review of Plant Physiology and Plant Molecular Biology* **51**: 501-531

**Ramanzin, M., Bailoni, L. and Beni, G. (1991)** Varietal differences in rumen degradation of barley, wheat and hard wheat straws. *Animal Production* **53**(2): 143-150

**RB209 (2010)** *Fertiliser manual (RB209) eighth edition*. Defra

**Rentizelas, A.A., Tolis, A.J. and Tatsiopoulos, I.P. (2009)** Logistics issues of biomass: the storage problem and the multi-biomass supply chain. *Renewable and Sustainable Energy Reviews* **13**: 887–894

**RL Project Consortium (2014)** *HGCA Recommended List cereal trials protocol 2013/2014*. Protocol CER 12-16 (updated February 2014). AHDB, Kenilworth, Warwickshire.

**Rogers, J.G. and Brammer, J.G (2009)** Analysis of transport costs for energy crops for use in biomass pyrolysis plant networks. *Biomass and Bioenergy* **33**: 1,367-1,375

**Rossi, A.M. and Hinrichs, C.C. (2011)** Hope and skepticism: farmer and local community views on the socio-economic benefits of agricultural bioenergy. *Biomass and Bioenergy* **35**: 1,418-1,428

**Rounsevell, M.D.A. and Jones, R.J.A. (1993)** A soil and agroclimatic model for estimating machinery work-days: the basic model and climatic sensitivity. *Soil and Tillage Research* **26**: 179-191

**Roy, J. (2014)** *Wheat straw for biofuel production*. PhD thesis. University of Nottingham.

**Scarlat, N., Martinov, M. and Dallemand, J.-F. (2010)** Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. *Waste Management* **30**: 1,889-1,897

**Shearman, V.J., Sylvester-Bradley, R., Scott, R.K. and Foulkes, M.J. (2005)** Physiological processes associated with wheat yield progress in the UK. *Crop Science* **45**: 175-185

**Skøtt, T. (2011)** *Straw to energy: status, technologies and innovation in Demark*. Innovation Network for Biomass.

**Smith, K.A., McTaggart, I.P. and Tsuruta, H. (1997)** Emissions of $N_20$ and NO associated with nitrogen fertilization in intensive agriculture, and the potential for mitigation. *Soil Use and Management* **13**: 296-304

**Sokhansanj, S., Kumar, A. & Turhollow, A.F. (2006)** Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass and Bioenergy* **30**: 838-847

**Tolera, A., Tsegaye, B. and Berg, T. (2008)** Effects of variety, cropping year, location and fertilizer application on nutritive value of durum wheat straw. *Journal of Animal Physiology and Animal Nutrition* **92**: 121-130

**Tonitto, C., David, M.B. and Drinkwater, L.E. (2006)** Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A metaanalysis of crop yield and N dynamics. *Agriculture, Ecosystems and Environment* **112**: 58-72

**Travis, A.J., Murison, S.D., Hirst, D.J., Walker, K.C. and Chesson, A. (1996)** Comparison of the anatomy and degradability of straw from varieties of wheat and barley that differ in susceptibility to lodging. *Journal of Agricultural Science* **127**: 1-10

**Tyndall, J.C., Berg E.J. and Colletti, J.P. (2011)** Corn stover as a biofuel feedstock in Iowa's bio-economy: an Iowa farmer survey. *Biomass and Bioenergy* **35**: 1,485-1,495

**Upreti, B.R. and van der Horst, D. (2004)** National renewable energy policy and local opposition in the UK: the failed development of a biomass electricity plant. *Biomass and Bioenergy* **26**: 61-69

**van Vuuren, D.P., Nakicenovic, N., Riahi, K., Brew-Hammond, A., Kammen, D., Modi, V., Nilsson, M. and Smith, K.R. (2012)** An energy vision: the transformation towards sustainability - interconnected challenges and solutions. *Current Opinion in Environmental Sustainability* **4**: 18-34

**Wang, L., Littlewood, J. and Murphy, R.J. (2013)** Environmental sustainability of bioethanol production from wheat straw in the UK. *Renewable and Sustainable Energy Reviews* **28**: 715-725

**Wiloso, E.I., Heijungs, R. and de Snoo, G.R. (2012)** LCA of second generation bioethanol: A review and some issues to be resolved for good LCA practice. *Renewable and Sustainable Energy Reviews* **16**: 5,295-5,308

**Wortmann, C., Klein, R., Wilhelm, W. and Shapiro, C. (2008)** *Harvesting Crop Residues*. Nebguide G1846, University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources (IANR).

**Wright, D. and Hughes, L. G. (1989)** The effects of site and variety on the in vitro digestibility of spring barley straw. *Plant Varieties and Seeds* **2**: 117-124

**Zhang, H., Fangel, J.U., Willats, W.G.T., Selig, M.J., Lindedam, J., Jørgensen, H. and Felby, C. (2014)** Assessment of leaf/stem ratio in wheat straw feedstock and impact on enzymatic conversion. *Global Change Biology Bioenergy* **6**(1): 90-96