AGRONOMIC, ECONOMIC AND ENVIRONMENTAL ANALYSES OF DUAL-PURPOSE WHEAT CULTIVARS FOR BIOENERGY

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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 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. 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.

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Abbreviations

AD – Anaerobic digestion

AFBI – Agri-Food and Biosciences Institute

AGDM – Above ground dry matter

CH_4 – Methane

CO_2 – Carbon dioxide

CO_2-eq – The radiative forcing strength of GHGs relative to the radiative strength of CO_2. Over a 100-year time frame the radiative forcing of methane (CH_4) is 25 times greater than CO_2 and nitrous oxide (N_2O) is 298 times greater than CO_2 (Forster et al., 2007, p. 212).

CV – Coefficient of variation

DPC – Dual-purpose cultivar

E15, E85 and E100 – Blends of petrol and ethanol with the approximate percentage of ethanol given as the number

EB – Environmental burden (i.e. emissions of pollutants and depletion of natural resources)

EU – European Union

FGB – First generation biofuel

GHG – Greenhouse gas

GM – Gross margin

HCG – Height at the centre of gravity

HGCA – Home Grown Cereals Authority

HI – Harvest Index

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

MC – Moisture content

N – Nitrogen

N_2O – Nitrous oxide

ODT – Oven dried tonne (feedstock at 0% moisture content)

PGR – Plant growth regulator

RED – Renewable Energy Directive

RTFW – Root failure wind speed. This is the minimum wind speed at which root lodging will occur.

SGB – Second-generation biofuel

SED – Standard error of the difference between means

SOC – Soil organic carbon

SOM – Soil organic matter

STFW – Stem failure wind speed. This is the minimum wind speed at which stem lodging will occur.

tkm – Tonne kilometres (weight of product being transported in tonnes divided by the distance it is being transported in kilometres).

UK – United Kingdom

USA – United States of America

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Chapter 1: Introduction

1.1 Research context

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 by the replacement of fossil fuels with alternative energy sources though this will require the development of multifarious technologies due to the scale and diversity of the uses of fossil fuels. The transport sector has been one of the major foci of clean energy technological developments because of its large share of oil consumption and greenhouse gas (GHG) emissions. In the European Union (EU), the transport sector has a 94% dependency on oil (European Commission, 2013) and in the United Kingdom (UK), the transport sector accounted for 36% of national energy consumption in 2012 (DECC, 2013a) and produced 118.5 Mt CO_2-eq in 2011 (DECC, 2013b).

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 (Cherubini & Strømman, 2011; Borrion et al., 2012a). There are a number of biofuel types and production methods. One category of biofuels currently being developed are cellulosic biofuels, also known as lignocellulosic biofuels or second-generation biofuels. These are produced from lignocellulosic material, such as the non-food parts of crops, forestry residue 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 (Advanced Ethanol Council, 2012).

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) 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.

1.2 Biofuels

Policy has had a strong influence on the development of the biofuel sector with the creation of a complex arrangement of incentives and restrictions (Smyth et al., 2010). In the EU there is considerable legislation relating to biofuel production and use, including binding targets for biofuel production and use; the purpose of which is to provide certainty for investors and, therefore, encourage further development of the sector (European Commission, 2009a). Directive 2003/30/EC (European Commission, 2003) required that EU countries replace 5.75% of transport fossil fuels with biofuels by 2010. This was replaced with the Renewable Energy Directive (RED; directive 2009/28/EC; European Commission, 2009a), which set a mandatory minimum target of 10% share of energy from renewable sources in transport fuels by

2020, with the majority of this expected to be from biofuels. This EU-wide legislation is implemented in the individual countries through national legislation, for example the Renewable Transport Fuel Obligation in the UK (DFT, 2011).

Alongside these factors driving the development of this sector, there is also significant concern about the impacts of this technology on the environment, in particular about the efficacy of using biofuels to reduce anthropogenic climate change. In the EU this has led to the inclusion in legislation of rules regarding the sourcing and production of biofuels and biofuel producers must show that their biofuels have significantly reduced GHG emissions relative to fossil fuel use (European Commission, 2009b).

Bioethanol and biodiesel are currently the only biofuels produced on an industrial scale (EurOberv'ER, 2011). Bioethanol is used as a petrol replacement; cars can use blends of petroleum and up to 17% bioethanol without any engine modifications (Difiglio, 1997) and with engine modifications cars can run on blends with considerably more bioethanol, such as E85, which contains 85% ethanol (Demirbas, 2008). Biodiesel can be used in blends of up to 20% in unmodified diesel engines but slight modifications might be needed for higher blends (NREL, 2009). It is estimated that in the EU, 5.7 billion litres of bioethanol were consumed in 2010 and 5.3 billion litres were produced, and 12.0 billion litres of biodiesel were consumed in 2010 with 10.7 billion litres produced (EurObserv'ER, 2011). Demand for biofuels is exceeding their supply with Europe necessitating imports from outside Europe. Biofuels contributed 4.4% of the total fuel use in the EU transport sector in 2010 (European Commission, 2012)

Biofuel production and use must increase to meet the legislative requirements and cellulosic biofuels will be mainly responsible for these increases. This is recognised in legislation, for example, with the binding nature of the EU targets being subject to cellulosic biofuels becoming commercialised (European Commission, 2009a). In the United States of America (USA), legislation has been set to include a minimum of 16 billion gallons of cellulosic biofuels in liquid transportation fuel mixes by 2022 (EISA, 2007). However, the yearly cellulosic biofuel requirements are set by the Environmental Protection Agency in the Renewable Fuel Standard program and requirements in 2013 have been revised down (EPA, 2013); this is due to the production of cellulosic biofuel not growing at the rate predicted in the original legislation (Anon, 2013a). Worldwide investment in biofuels was approximately US$5 billion in 2012; however this was 40% lower than the previous year, partly in response to policy uncertainty (UNEP, 2013). These points demonstrate an interesting interplay between policy and biofuel development: the development of the cellulosic biofuel sector is dependent on policy certainty yet at the same time biofuel policy is dependent upon progression in the development of cellulosic biofuels that is itself inherently uncertain.

1.2.1 First-generation biofuels

Biofuels can be divided into first-generation biofuels (FGBs) and second-generation biofuels (SGBs) based on the feedstock used (Larson, 2008). The feedstocks for FGBs are from the edible part of plants and these can be divided into three categories: 1) sucrose-containing materials such as sugar cane; 2) starchy materials such as corn and wheat grains; 3) vegetable oils of oleaginous plants, such as oilseed rape and oil palm, and animal fats. SGBs are produced from lignocellulosic material.

At the moment 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). One concern is competition with food production, which is believed to have contributed to the recent increases in food prices (Mitchell, 2008). Another concern is *indirect land-use change*, which is where the use of farmland for biofuel feedstock production has required 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.

1.2.2 Second-generation biofuels

Concerns about FGBs have led to greater emphasis on developing SGBs as it is hoped that these will provide an energy source with lower environmental impacts, without negative societal effects (Gnansounou, 2010).

The lignocellulosic material that SGBs are produced from is comprised of the long-chain polymers lignin, cellulose and hemi-cellulose, along with a small amount of soluble substrates and ash that make up the plant cell wall (Talebnia et al., 2010). All lignocellulosic material can be used as a feedstock for biofuel production; however, there are several groups of lignocellulosic biomass that are being targeted for biofuel production: crop residues, pulpwood and forestry residues, dedicated energy crops and municipal waste (Tilman et al., 2009). These materials differ in their properties and are suited to different conversion technologies. The feedstocks that will be used depend on availability; in the USA the dominant feedstock for cellulosic biofuels is maize stover (Somerville et al., 2010) whereas in the UK dominant feedstocks are wheat, barley and oilseed rape residues (LACE, 2013).

There are two main pathways for the production of cellulosic biofuels: the thermochemical route and the biochemical (also known as the biological). The thermochemical route utilises pyrolysis or gasification technologies, which use high pressures and temperatures, to convert lignocellulosic material into intermediate compounds such as synthesis gas (carbon monoxide and molecular hydrogen), which are then converted into long chain biofuels (Sims et al., 2008). The biochemical route utilises enzymes and micro-organisms to ferment cellulose into alcohols. There are four stages: 1) pretreatment to make the cellulose accessible; 2) enzymatic hydrolysation of the cellulose to glucose; 3) fermentation of the glucose to produce alcohol; and 4) distillation to produce neat alcohol (Wright & Brown, 2007). Depending on the production method, hemi-cellulose may also be hydrolysed and converted into biofuel or alternative products. The lignin is recalcitrant to chemical breakdown and is instead often combusted to produce heat and energy for running the biorefinery.

The optimum production route depends on the feedstock; for example, the thermochemical production route is better suited to soft wood feedstocks whilst the biochemical route is better suited to crop residues (Foust et al., 2009). The BBSRC-funded LACE project, run by a consortium of research organisations, led by the University of Nottingham, is researching the use of the biochemical pathway to produce bioethanol from wheat straw (see LACE, 2013). As this current project is associated with the LACE project, it will focus on the production of ethanol using the biochemical pathway.

One of the reasons that cellulosic biofuels have taken so long to become commercialised is that lignocellulosic material is very recalcitrant to breakdown by mechanical and microbial forces, and, therefore, there is a high energy demand during the pretreatment stage (Talebnia et al., 2010). Considerable work is being undertaken to achieve the technological breakthroughs required to make cellulosic biofuels economically competitive with fossil fuels (Gnansounou, 2010). A number of pilot plants have been built to research into improvement (e.g. the Inbicon demonstration plant, Denmark; Larsen et al., 2012a). The world’s first commercial plant started operating in 2012 (Beta Renewables’ Crescentino plant in Italy) and several other commercial plants are in development or being constructed (Advanced Ethanol Council, 2012).

1.2.3 Wheat as dual-purpose food and energy crop

Authors, such as de Lion & Coors (2008) and Salas Fernandez et al. (2009), have suggested the breeding of cultivars that have characteristics beneficial to both food production and energy production, such as both high grain and residue yields. Lorenz et al. (2010) investigated the relationship between maize grain yields and stover yields and found a positive correlation, suggesting that increasing stover yields for bioenergy production would not come at the expense of grain yields. Harris & DeBolt (2010) suggested genetically engineering plants to have improved traits for conversion to biofuel.

Wheat is the most widely grown crop in the UK (FAOSTAT, 2013). Due to low value of crop residues, crop breeding has focused on the grain component. Unlike maize, where the stover yields increased in tandem with the grain yields, wheat grain yield increases came at the expense of straw yield (Austin et al., 1980). With the development of a market for biomass for SGB production, the price of crop residues could increase leading to a focus on increasing the yields of these to maximise the overall value of a crop. Growing dual-purpose cultivars (DPCs) that are optimised to gain the highest value for both grain and straw components could both increase feedstock availability for biofuel production as well as increase farmer income.

Although previous authors have suggested developing new cultivars, there is potential benefit from investigating the potential for DPCs from existing cultivars. The potential bioethanol yields (i.e. a cultivar's digestibility) from current wheat cultivars have been investigated (see **section 2.2.3**) but there is only limited work considering straw yields (e.g. Larsen et al., 2012b). Roy (2014) looked at the cultivar variability of the following four traits that are thought to be important to a dual-purpose food and energy wheat cultivar: grain yield, straw yield, lodging resistance (see **section 2.2.2**), and straw digestibility. There are trade-offs between these traits. For example, the reason for looking at lodging resistance, which is the ability of a plant to withstand being displaced from the vertical by wind, is that there is a potential trade-offs between that and straw yield and straw digestibility. Roy (2014) found that there were differences in these traits in current cultivars but trade-offs between them are harder to identify. Two cultivars (Quartz and Cordiale) were identified as good candidates for this role; they had high straw and grain yields in the years they were analysed, as well as high stem glucose levels and good lodging resistance. Further work is needed to determine the potential benefits of growing DPCs and identify suitable candidates amongst currently grown cultivars for use as DPCs.

1.3 Project outline

This research project is focused on quantifying traits in current cultivars for the purpose of selecting dual-purpose food and energy wheat cultivars, as well as quantifying the environmental and economic impacts resulting from the use of dual-purpose cultivars. It will increase understanding that will facilitate the development of a market for cellulosic material and inform the direction of future crop breeding research and policy.

Project objectives

The project has eight major objectives:

- To identify agronomic and processing differences between wheat cultivars.
- To investigate how agronomic practices can influence the biofuel feedstock potential of wheat cultivars.
- To quantify the economic benefits of dual-purpose cultivars to farmers.
- To quantify haulage costs for transporting straw from the farm to the biorefinery.
- To investigate potential differences in the environmental impacts between cultivars using a Life Cycle Assessment (LCA) approach.
- To quantify current straw use and future availability of straw use for biofuel production.
- To improve understanding of farmer attitudes towards the straw market and future farmer decision making should a new straw market develop.
- To provide advice based on the project findings to the various stakeholders in the biofuel supply chain.

The objectives are further divided into a number of aims, which are presented in each experimental chapter.

Project components

To achieve these objectives the project has five major components:

1. Field experiments for quantification of yields and quality characteristics of multiple cultivars of winter wheat grown under different management practices, building on previous work by Roy (2014).
2. Economic model for quantification of the potential gross margins of DPCs to farmers.
3. Logistics model for quantification of the transport costs for collection of straw.
4. Life cycle assessment for quantification of the environmental footprints of different DPCs.
5. Survey to determine current wheat straw use and farmers' attitudes and future responses towards the development of a cellulosic biofuel market, in particular, influences on decision making with regards to the selection of cultivars.

1.4 Thesis Contents

The thesis is divided into seven chapters. Following this introductory chapter, **Chapter 2** covers the field trials and assessment of the cultivars and associated agronomic practices. **Chapters 3** and **4** deal with the straw supply chain; **Chapter 3** is an economic assessment of the production and baling of straw from DPCs whilst **Chapter 4** examines the logistics of transporting these cultivars from the farm to the refinery. **Chapter 5** presents the Life Cycle Assessment of the dual-purpose cultivars. **Chapter 6** covers the farmer survey and farmer decision making analysis. **Chapter 7** provides a discussion of how the results of each research area combine and places these in context with the current status of the biofuel and agricultural sectors. Due to the range of topics being addressed in this study, each chapter starts with a review of the relevant literature for the topic of that chapter.

Chapter 2: Dual-purpose cultivar traits

2.1 Introduction

The concept of a dual-purpose (DPC) food and energy wheat cultivar was introduced in the previous chapter. As part of this investigation, field experiments were used to quantify key data relating to the traits of a DPC. In this chapter, the experimental design, results and findings are presented and the findings are then used to inform subsequent chapters.

2.2 Literature review

This literature review considers the four key traits of a DPC. These are discussed individually, as well as the interactions between them. Firstly it will consider straw yields, followed by lodging and finally straw digestibility. 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., 2012b). 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.

2.2.1.1 Factors influencing straw yields

Straw yields are influenced by a number of environmental factors including sowing date and sowing density (Donaldson et al., 2001), nitrogen (N) and water availability (Engel et al., 2003), and fungal infections and, therefore, fungicide treatment (Jørgensen & Olesen, 2002). Straw yields also vary with cultivar (Donaldson et al., 2001; Engel et al., 2003; Skøtt, 2011; Larsen et al., 2012b). There are also interactions between these environmental and genetic factors (Engel et al., 2003).

Climatic conditions are thought to have a large influence on straw yields. Large-scale assessment of wheat straw and grain yields (see Larsen et al., 2012b, for references) found that there was also considerable temporal variation, with 46% variation in the yearly averages, which was hypothesised to be a result of differences in weather between years. Roy (2014) found that straw yields differed between years; the reason for the difference between years was unclear but the lower yields could have resulted from there being lower rainfall that year.

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., 2012b); 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., 2012b); 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.

2.2.1.2 Straw yields

Unlike with grain, where almost all is collected at harvest, a significant proportion of the straw is left on the field after baling due to mechanical limitations of harvesting equipment. This material includes the stubble and smaller pieces of material such as leaf and chaff (Sokhansanj et al., 2008a). The proportion of straw collected varies with equipment used (Allen, 1988; Boyden et al., 2001). Lowering the height of the combine harvester header can increase the proportion of straw collected (Boyden et al., 2001) but this increases combine harvesting time and fuel use (Kehayov et al., 2004). It is suggested that under standard conditions approximately 50% of the non-grain biomass can be baled (Sylvester-Bradley et al., 2008). [N.B. As the baled straw yield differs from the total straw yield (i.e. the whole stem and leaf yield) the term ‘straw yield’ could cause confusion as to what it is referring to. In this thesis, straw yield refers to the yield of straw that is baled. When referring to the whole stem and leaf yield this is referred to as total straw yield.]

As well as mechanical limitations, the proportion of straw that is baled depends on how much can be removed without negative impacts on the soil. It is generally recommended that some crop residue is left on the field after baling (Lafond et al., 2009); this is because it provides a number of benefits including protection against soil erosion (Lindstrom, 1986), return of nutrients, improved water quality (Lal, 2004), C sequestration potential (see **Chapter 5**) and maintenance of soil organic matter level (SOM; Powlson et al., 2011). SOM in particular is important as it can positively influence agronomic productivity through improved soil structure (Lal, 2004), soil moisture retention (Wilhelm et al., 1986) and microbial processes (Bending et al., 2002).

However, the benefits that returning straw provide are highly dependent on the conditions of the land including its current SOM, climatic conditions and soil type, amongst other factors (Kludze et al., 2013). This means that the amount of straw that can be baled and the frequency of baling depend on location. This variability means that it is difficult to recommend how much residue should be left on the field. Some general guidelines are available and in the US there are a number of tools to help farmers decide on the amount of residue to remove (e.g. RUSLE, WEQ and the Soil Conditioning Index; see Andrews, 2006). However, there appears to be little information available for farmers in the UK on how much straw they can remove. For the current project, the question of the sustainability of straw removal is not extensively addressed. In general, it is assumed that straw is only harvested where it is sustainable to do so and some material is left on the field (i.e. the stubble and chaff) and this is sufficient to prevent negative impacts on the soil. However, in some subsequent chapters the question of sustainability of straw removal is considered.

Straw will only be baled if there is a market available. In many places straw production exceeds demand (Copeland & Turley, 2008). There are also a number of factors that farmers take into account when making decisions about whether to bale, such as impacts on the next crop in the rotation. These are presented in **Chapter 3** and **Chapter 6**.

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, these 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, 2013b). 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.

2.2.1.3 Plant height

In general, there is a strong correlation between straw yield and plant height (e.g. Engel et al., 2003; Larsen et al., 2012b; Long & McCallum, 2013) and this relationship is important as plant height is strongly linked to lodging susceptibility (see **section 2.2.2**). The relationship between plant height and straw yield offers an opportunity to predict straw yield from plant height. Several studies have calculated relationships between straw yield and straw height. Long & McCallum (2013) found a strong linear relationship between straw yield and plant height (**Eq. 2.1**). However, Larsen et al. (2012b) found a curved relationship between straw yield and straw length (**Eq. 2.2**). Engel et al. (2003) found that an equation that incorporated grain yield and soil N availability gave the best calculation of straw yield from straw height (**Eq. 2.3**).

$$SY = (0.0073 \times SH) - 0.4 \qquad \textbf{Eq. 2.1}$$

$$SY = 1 \div \left((-0.00039 \times SH) + 0.592\right) \qquad \textbf{Eq. 2.2}$$

$$SY = -3.0492 + (0.728 \times GY) + (0.00513 \times SH) + (0.22301 \times STN) \quad \textbf{Eq. 2.3}$$

Where: *SY* = straw yield (t ha^{-1}); *SH* = straw height (mm); *GY* = grain yield (t ha^{-1}); *STN* = straw nitrogen (g kg^{-1})

These equations demonstrate that, even though there is a positive relationship between height and yield, it is highly variable and, furthermore, these equations are only applicable for the cultivars measured in those studies and cannot be used more widely. They suggest that amongst current cultivars, selecting cultivars with higher straw yields will mean selecting taller cultivars. However, this relationship is not always seen; for example, Donaldson et al. (2001) found that the straw yields of a semi-dwarf cultivar did not differ significantly from standard height or tall cultivars. It may be possible to find cultivars that have high straw yield whilst also maintaining good lodging resistance through having shorter stems. Also, increasing straw yield has not been the focus of plant breeding attempts and it may be possible to increase straw yield without increasing height.

Crop management can influence the relationship between straw yield and straw length. Plant growth regulators (PGRs) are synthetic compounds that are used to reduce stem height to increase lodging resistance. The potential influence of this on straw and grain yields in discussed in **section 2.2.2**.

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.

The relationship between straw and grain yields is variable. Under conditions without severe stress or abnormal chemical treatments the relationship can be reasonably fixed as demonstrated by a consistency in HI (as reviewed by Hay, 1995). However, under other environmental and management conditions HI can fluctuate significantly, particularly under adverse field conditions and crop stress (e.g. Gallagher & Biscoe, 1978). The stability of HI is also influenced by cultivar (Peltonen-Sainio et al., 2008). Management practices can influence HI. For example, HI differs between main stem and tillers (Hay, 1995) so tillering rate, which is strongly influenced by management and environment (Mahmoud & Osman, 1981), will affect overall HI.

HI is also not a perfect indication of the amount of straw available as it includes chaff, the majority of which is likely to be lost during baling, as well as stubble. Instead, residue-to-grain ratios are often used in predicting straw yield from grain yields for trials where straw yield has not been measured, usually assuming that there is a direct or linear relationship between grain and straw yields (Engel et al., 2003). There is considerable variation in the literature for straw-to-grain ratios: in assessing the literature Scarlat et al. (2010) found a range of 0.8 to 1.8 for winter wheat; an assessment of biomass yields in Denmark found the average ratio varied from 0.48 to 0.64 (see Larsen et al., 2012b, for references); whilst an assessment in hard red spring wheat found that straw to grain ratios ranged from 0.91 to 2.37 (Engel et al., 2003).

The reason for the large range of values is that there a number of factors that influence these ratios. These factors include: cultivar choice (Skøtt, 2011), with taller cultivars showing greater variability (Engel et al., 2003); farming practices (e.g. tillage; Linden et al., 2000); environmental factors such as N and water availability (Donaldson et al., 2001; Engel et al., 2003); and type of combine harvester used (Stumborg et al., 1996). The environmental factors can influence the grain and straw components differently and it has been suggested that the grain component is more stable under stress conditions (Linden et al., 2000). Because of the variation with cultivar and location specific factors, these ratios need to be calculated for individual cultivars and locations to accurately predict straw yield from grain yield.

Although residue-to-grain ratios are commonly used in estimating straw availability, Scarlat et al. (2010) suggests that the relationship between the residue-to-grain ratios and grain yield is a more appropriate method of estimating residue yield from grain yield. Plotting the values from available data in the literature, they found that for wheat, the appropriate ratio could be estimated using **Eq. 2.4**. This suggests that as grain yield increases the ratio of straw to grain decreases (i.e. the amount of straw relative to grain decreases as grain yield increases).

$$R = -0.3629 \times \ln(GY) + 1.6057 \qquad \textbf{Eq. 2.4}$$

Where: *R* = is the residue-to-grain ratio; *GY* = grain yield (t ha^{-1}).

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.

2.2.2.1 The causes of lodging

Lodging results from interactions between the plant, wind, rain and soil (Baker et al., 1998) and, due to the complexities of these interactions, it is difficult to have a complete understanding of what controls lodging. There are two distinct types of lodging: stem lodging and root lodging (Berry et al., 2004). Stem lodging is caused by the breaking of lower culm internodes, and occurs when the stem bending moment exceeds the strength of the stem base, whilst root lodging is caused by disturbance to the root-soil interface, and occurs when the total bending moment of a plant exceeds the strength of the root-soil interface.

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 (**Fig. 2.1a**). The natural frequency can be thought of as how spring-like the stem is in returning to its upright position after displacement; the quicker it returns the lower the leverage force. The strength of the stem base is based on the stem material strength, which is determined by the breaking strength of the stem (tensile failure strength), internode length, and the stem radius and wall width of the lower internodes (**Fig. 2.1b**). The root-soil interface strength is based on the root plate spread and depth (**Fig. 2.1c**). 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}.

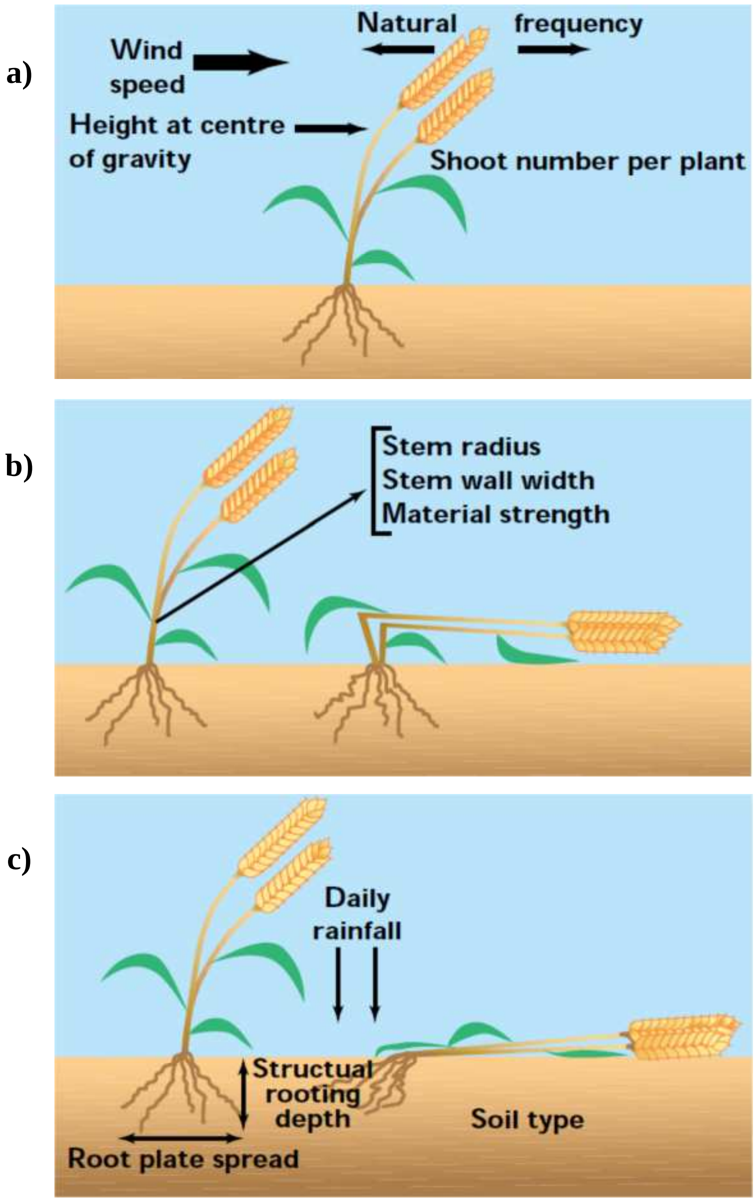


Figure 2.1: Lodging model representation of a) leverage force; b) stem strength; and c) anchorage strength. Figures taken from HGCA (1999).

Management practices, such as fertiliser application, also have a large impact on plant structure and, therefore, lodging susceptibility. High residual N levels lead to characteristics that increase lodging, in particular increasing the HCG (Berry et al., 2000). Reducing spring N application produces plants with shorter stems, which leads to reduced lodging susceptibility. Increased N application has been shown to affect the mechanical properties of the stem and root system; lowering the stem strength and reducing the number and strength of coronal roots (Crook & Ennos, 1995).

A crop's environment has a large influence on the susceptibility and severity of lodging. This can be seen by the uneven distribution of lodging within a field reflecting the non-uniformity of the field (Pinthus, 1973). This spatial variation at the field level could be due to management such as overlapping seed drilling or fertiliser spreading, or variation in soils or topography. The soil composition and structure has a large impact on root lodging susceptibility; Baker et al.'s (1998) model contains soil clay content and soil moisture parameters as these influence soil anchorage strength.

Other environmental-genetic factors affect lodging susceptibility such as crop disease. For example, certain diseases, such as eyespot, can weaken the plant stem leading to greater lodging susceptibility (Pinthus, 1973). Cultivars vary in their susceptibility to eyespot and it is one of the diseases for which cultivar resistance is scored in the HGCA RLs.

2.2.2.2 Reducing lodging risk

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 (see **Chapter 6**) and data is provided for lodging resistance on the recommended lists (e.g. HGCA 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 N, 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.

As well as the main effect on reducing height, PGRs can have other influences on crop traits. With the reduction in height it would be expected that straw yields would also decrease; however, there are few studies that have compared straw yields between PGR treatments. Bragg et al. (1984) found that although chlormequat application reduced plant height, it did not significantly influence straw or grain yields. Roy (2014) found that chlormequat did not influence total biomass, total straw yield, or HI. In a glasshouse trial of cereals, Rajala & Peltonen-Sainio (2001) found that PGR application reduced main stem growth and weight; however, this was for an early application of PGRs and measurements were taken 14 days after application.

Berry et al. (2004) reviewed data from studies investigating the effect of chlormequat on grain yield and yield components in the absence of lodging. The effect on grain yield was variable with some studies finding increases whilst others found no change or even decreases in yield. A limited number of studies found that the application of chlormequat at various growth stages increased ear number; however, this was highly variable and not seen in other studies (see Berry et al., 2004). Roy (2014) did not find chlormequat application significantly affected grain yield or ear number. The effects of PGR application vary greatly with the GS at application and the effectiveness PGR application vary with the weather conditions during and after application (Runkle, 2010).

PGRs might also influence other characteristics associated with lodging susceptibility; however, once again these are not consistently seen. Berry et al. (2000) found that chlormequat slightly reduced the material strength of wheat stems, and Crook & Ennos (1995) found that an application of chlormequat followed by two other PGRs reduced stem strength in wheat. No consistent PGR effects have been found on the diameter and wall width of the stem of oats or wheat (Crook & Ennos, 1995; Berry et al., 2000). Neither Crook & Ennos (1995) nor Berry et al. (2000) observed any effects of PGR treatment on the spread of the root plate and rigidity of the surface roots. Roy (2014) did not find any influence on lower internode traits resulting from the application of chlormequat.

2.2.2.3 The cost of lodging

The effects of lodging vary greatly with many lodging events only causing small grain yield reductions whilst others can lead to reductions of 80%, causing a significant economic loss to farmers (Berry et al., 2004). Reductions in grain yield are likely to be through lower carbon assimilation resulting from a reduction in radiation interception (Berry et al., 2004). Grain quality effects include a reduction in Hagberg falling number, which limits the uses of the grain and likelihood of it achieving a premium price (Berry et al., 2004; Berry et al., 2007). As well as reducing yield and quality, lodging events can also increase farm operation costs, such as combine harvesting costs (ABC, 2013) and slow the harvest (Refsgaard et al., 2002). Lodging can also reduce moisture loss from the grain prior to harvest, increasing the need for grain drying post-harvest (Baker et al., 1998).

Lodging can occur at any time during the growing period but it is most likely during the two or three months preceding harvest (Berry et al., 2003a). The timing of the lodging event has a large impact on the effect on grain yield and quality. If the lodging event occurs early in the growing period, prior to grain filling, then the plants have time to recover. Lodging during grain filling can cause the greatest yield losses, with the largest impacts resulting from lodging early in the grain filling stage and diminishing the later lodging occurs during grain filling. Lodging towards harvest can reduce grain quality and increase harvesting difficulties.

It is estimated that, on average, severe lodging occurs in UK wheat crops every 3 to 4 years when 15-20% of the area lodges (Berry et al., 2004). It is estimated that in 1992, severe lodging in the UK cost growers up to £130 million (Sterling et al., 2003). To mitigate lodging risk, farmers apply PGRs with each application costing up to £18 application^{-1} ha^{-1} depending on the chemical used (ABC, 2013).

2.2.2.4 Straw yield and lodging susceptibility

The likelihood of trade-offs between straw yields and lodging risk is suggested by the correlations between plant height and straw yield (e.g. Engel et al., 2003) and between plant height and lodging (e.g. Baker et al., 1998; Berry et al., 2003c). This is supported by Berry (1998) and Berry et al. (2004) who showed that increasing biomass leads to a higher HCG, hence increasing lodging risk. However, distribution of dry matter along the stem is important in the overall influence of biomass on HCG (Berry et al., 2004). There appears to be no work comparing straw yield to lodging risk and only limited work considering the impact of PGRs on straw yield and, therefore, it is not possible to compare the trade-off between straw yields and lodging resistance from previous studies.

In developing higher-yielding lodging resistant wheat cultivars, Berry et al. (2007) suggest that to increase material strength of the stem requires an increase in stem biomass. This might mean that increasing straw yields may be possible without increasing the risk of lodging; however, Berry et al. suggest this would lead to competition between grain filling and straw biomass. It is unclear whether increasing the biomass for the lower internodes would actually allow a greater volume of straw to be harvested; if the increase is in the lower stem then the majority of this would be below the combine cutter height. Further work is needed to explore the relationship between lodging susceptibility and straw yields.

2.2.3 Wheat straw digestibility

During the production of SGBs, it will not be economical to convert all the cellulose into ethanol. 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.

Plant material varies in digestibility due to variation in the proportions of lignin, cellulose and hemi-cellulose composing the cell wall (Pauly & Keegstra, 2008), as well as cell and tissue types within a plant differing in digestibility based on their location within the plant and by their anatomical features (Travis et al., 1996). Characteristics such as lignin content and cellulose crystallinity have been shown to influence digestibility (for a summary of characteristics see Chang & Holtzapple, 2000).

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 the variability within current cultivars and the application of these cultivar differences to the production of biofuels (e.g. Lindedam et al., 2012b).

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.

This genetic and environmental variation in digestibility can, in part, be accounted for by the ratio of the different plant components. Leaf material has been shown to be more digestible than stem resulting in overall digestibility varying with the leaf-to-stem ratio (Kernan et al., 1984; Capper, 1988; Tolera et al., 2008; Zhang et al., 2014). Cultivars vary in the proportion of the different components, such as the amount of stem and leaves (i.e. the leaf-to-stem ratio; Capper, 1988) so the proportion of each component determines the overall digestibility. However, Ramanzin et al. (1991) found that this ratio was only of minor importance in the comparison of overall digestibility of cultivars as the digestibility of individual components varied between cultivars as well. The importance of this ratio is lessened by the fact that most leaf material tends to be lost during harvesting so will not be present in the baled straw sent for biofuel processing (Hoskinson & Hess, 2004).

2.2.3.1 Digestibility and biofuel production

Although the animal and mushroom studies give an indication of the ease with which the lignocellulosic material is broken down, the relevance to the production of biofuels has been considered in papers specifically focussing on the breakdown of the material for conversion to biofuel. Several studies have compared the digestibility between wheat cultivars and these are discussed below. Various chemical assays have been used in the following studies so it is not possible to make direct comparisons of sugar yields between studies.

Jenson et al. (2011) compared the digestibility of 106 currently grown or new wheat cultivars grown at two locations without intra-location replication. They found significant differences between the digestibilities of the cultivars with sugar release per unit of material ranging from 258 to 407 g kg^{-1} of dry matter, and differences between locations. The ten most digestible cultivars had an average of 6.1% higher sugar levels than the average of all of the cultivars. They suggested that there was 29% heritability of digestibility but without replication it is unclear how fixed these results are and how reliable the estimates of heritability are. Other plant characteristics, such as leaf-to-stem ratio, were not measured so digestibility level cannot be compared to these.

Lindedam et al. (2010) compared five wheat cultivars grown at two locations. Pilot plant-scale pretreatment was used in an effort to determine whether differences in digestibility seen in laboratory-scale assays were also seen in larger-scale assessments. Cultivars responded differently to pretreatment conditions meaning that digestibility is dependent on processing conditions. Under some pretreatment conditions, a significant difference was seen between cultivars. Though no statistical results are given, digestibility appeared to be higher at one site than the other suggesting an environmental influence on digestibility.

Lindedam et al. (2012) measured the polymer composition and sugar yields of 20 wheat cultivars, grown at two locations in one year with two randomised blocks per site. They found that there was a significant difference in sugar release between the cultivars with up to 26% digestibility difference between cultivars, but there was no correlation between grain yield and digestibility. The authors suggest that heritability of sugar release is 57% and from the range of sugar released in the assessed cultivars (26%) they predict that overall sugar yields could be increased by 15% above the current average.

Larsen et al. (2012b) compared a number of winter wheat cultivars over two years in multiple locations (two in the first year and three in the second). There was a range of 9% in total sugar release between cultivars and up to 7% between locations but these differences were insignificant. There was no significant relationship between straw yield and digestibility.

Roy (2014) assessed the digestibility of multiple winter wheat cultivars over two years and found that there were significant differences. The glucose yield after pretreatment varied with cultivar and year (ranging from 244 to 374 g kg^{-1} of dry matter in 2010 and 315 to 404 g kg^{-1} of dry matter in 2011) and this was unrelated to the total amount of glucose present in the material.

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. However, the experimental design is likely to only capture some environmental variability as only a limited number of locations were compared, often without intra-location replication, and only Larsen et al. (2012b) and Roy (2014) collected data for more than a single growing season. This suggests that these studies have not fully quantified environmental variability in digestibility and that the heritability of digestibility characteristics might not be as strong as the studies suggested.

There is disagreement in the literature regarding the relationship between plant height and digestibility. Lindedam et al. (2012) found that sugar release increased with plant height (which does not appear to be related to the ratio of stem, leaf blade and chaff) whereas Jensen et al. (2011) and Roy (2014) found sugar release decreased with plant height. These studies did not determine what was causing these correlations but Lindedam et al. (2012) suggested that the results in their study was due to the greater growth of the stem meaning that the tissue was easier to convert, rather than resulting from a difference in leaf-to-stem ratio.

2.2.3.2 Crop management and digestibility

Agronomic practices could potentially influence the digestibility of straw through influencing the proportions of plant components or through other processes acting at smaller scales. The effect of agronomic practices on digestibility has been investigated both for biofuel production and in other studies, though there is little work looking at the effects of agronomic practices on individual component digestibility. In barley, sowing date influenced the digestibility through changing the leaf-to-stem ratio (Capper et al., 1992). Fertiliser has an influence: Flachowsky et al. (1993) found that very high applications of N led to higher digestibility; Tolera et al. (2008) found that increasing N and P fertiliser application tended to increase dry matter loss during soaking in warm water, but did not change dry matter loss through other digestibility assessment methods; and Kernan et al. (1984) found that increasing N fertiliser led to a difference in the digestibility of leaf but not stem or chaff; the actual difference between fertiliser treatments was very small. However, Murozuka et al. (2014) found that higher N fertiliser application rate led to lower straw digestibility. It is possible that N has an influence on the overall digestibility through changing the proportions of plant components but might also have a small effect on the digestibility of leaf material.

Several studies have considered the effect of PGRs on wheat straw digestibility. Sharma et al. (2000) found that PGRs, when applied with fungicide, increased digestibility; however, the independent effects of the PGR and fungicides were not determined. Savoie et al. (1994) did not find a consistent effect on digestibility but PGRs were only applied 62 days before harvest so it is unlikely they had a large influence on plant form. Roy (2014) found that chlormequat application did not significantly affect digestibility. These studies suggest that the influence of PGRs on digestibility is minor and highly variable. It would be expected that PGRs would lead to an increase in digestibility through a reduction of the leaf-to-stem ratio but further work is needed to investigate this.

Digestibility has been compared to other crop traits. Ramanzin et al. (1991) did not find significant correlations between straw digestibility and plant height, days from sowing to heading, and grain production and quality. Tolera et al. (2008) found that, of the straw quality traits assessed, only crude protein content was negatively correlated with grain and straw yield. Habib et al. (1995) did not find a relationship between grain yield and straw digestibility suggesting that it should be possible to select wheat cultivars that produce high digestibility straw without sacrificing grain yield. These observations demonstrate that wheat cultivars can be identified that combine the desirable characteristics of high grain yield and superior straw digestibility.

2.2.3.3 Lodging and digestibility trade-off

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. As discussed above, studies differ in their conclusions about this. 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. Work is needed to consider whether there are trade-offs between lodging resistance, straw digestibility and straw yields, as well as whether management practices used to maximise a particular trait might cause a reduction in another trait (e.g. assessing whether increasing lodging resistance through the use of PGRs leads to lower straw yields and/or digestibility).

2.3 Chapter aims

The aims of the experimental work of this chapter are:

Biomass

- Quantify total straw and grain yields for multiple wheat cultivars.
- Investigate how straw mass varies along the stem to assess the influence of combine header height on harvestable straw yields.
- Determine if there is a relationship between straw length and straw yield.
- Determine if there is a relationship between grain and straw yields.
- Investigate the influence of chlormequat application and different N fertiliser application rates on biomass characteristics.

Lodging

- Determine how lodging susceptibility is influenced by cultivar, chlormequat application and different N fertiliser application rates.
- Determine how plant form varies with cultivar, PGR and nitrogen fertiliser application.

Digestibility

- Determine how digestibility is influenced by cultivar, chlormequat application and different N fertiliser application rates.
- Compare the digestibilities of different plant components.
- Compare lodging traits with stem digestibility and address the question of whether there is a trade-off between susceptibility resistance and digestibility.

2.4 Methodology

2.4.1 Field experiments

Field experiments were conducted at the University of Nottingham's Farm at Sutton Bonington (52°50'N, 1°15'W) between 2009 and 2012. For the overall biomass project, three field experiments were conducted but the current project was only involved in the second and third experiments. The first field experiment was conducted by Johar Roy as part of his PhD project and involved the assessment of 40 wheat cultivars for specific properties relating to a DPC. The second field experiment was conducted primarily as part of Roy

(2014) with a contribution from the current project for lodging and biomass assessments. The third field experiment was conducted solely for the current project. These two field experiments are described in detail below.

The majority of the results from the second field experiment are presented in Roy (2014) but some of the data collected in conjunction with that field experiment are presented in this thesis. Data from Roy (2014) is used to compare cultivar characteristics across the three years.

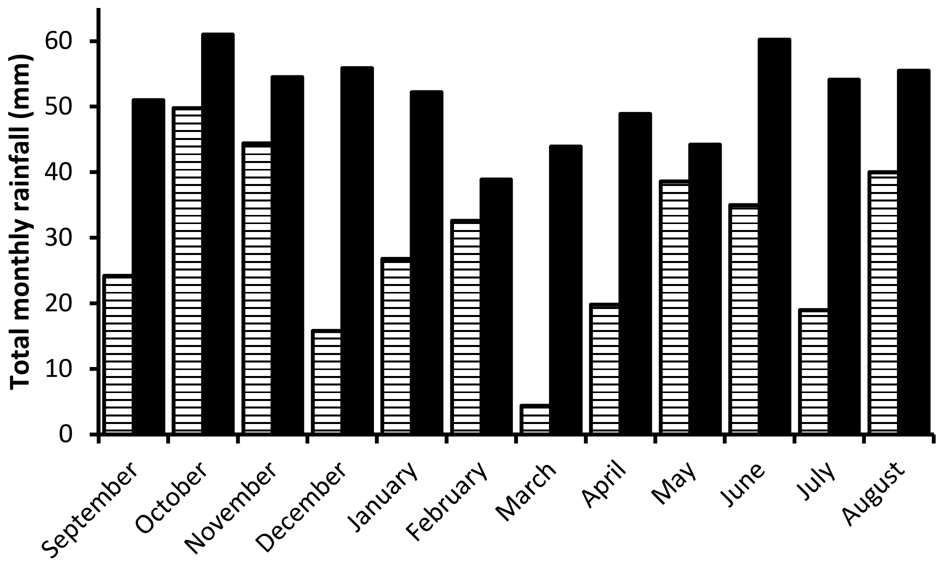
2.4.1.1 Field experiment: 2010-11

This field experiment was primarily run as part of the related project and the design and results are described in Roy (2014). The experiment involved 15 cultivars (**Table 2.1**); of which 14 were from the previous year's experiment with an additional cultivar, Glasgow, added due to its reported high biomass production. These were grown in a split-plot design with (PGR+) and without (PGR-) the PGR chlormequat. The experiment was organised in three blocks with the cultivars randomly distributed within the main-plots. Standard practices for fertilisers and pesticides (other than PGRs) were used. A field experiment plan and a schedule of inputs and management practices used are given in **Appendices 1 and 2**, respectively. The weather for the growing season is given in **Fig. 2.2**; there was low rainfall throughout the growing season, but especially in spring.

Table 2.1: Cultivars grown in the first field experiment. Adapted from Roy (2014) based on data from the HGCA RLs. N.B. Maris Widgeon predates HGCA RLs so data is not available on these key parameters; the date refers to the year of introduction (Austin et al., 1980).

Cultivar	NABIM group	Resistance to lodging without PGR	Resistance to lodging with PGR	Height without PGR (cm)	Height with PGR (cm)	Year first listed
Hereward	1	8	9	88	-	1991
Mascot	1	6	8	93	84	2006
Xi19	1	4	6	97	88	2002
Battalion	2	7	8	88	82	2007
Cordiale	2	8	9	82	76	2004
Sterling	2	6.7	8.3	80	-	2010
Invicta	3	7.2	7.5	93	86	2010
Riband	3	8	8	89	-	1989
Zebedee	3	6	6	87	84	2007
Ambrosia	4	7	8	88	80	2005
Glasgow	4	6	8	85	74	2005
Grafton	4	9	9	79	72	2009
Istabraq	4	6	7	96	88	2004
Quartz	4	9	9	75	-	2009
Maris Widgeon	-	-	-	-	-	1964

a



b

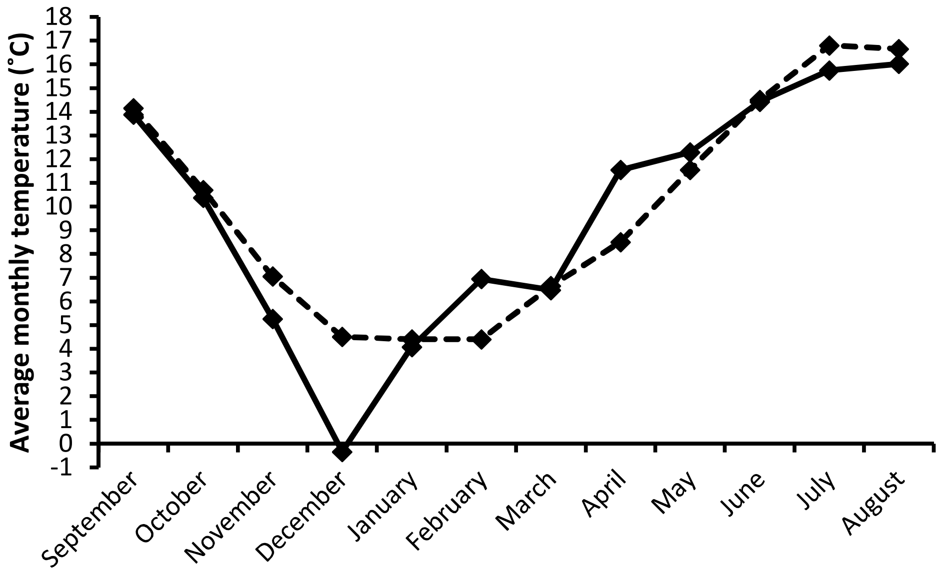


Figure 2.2a, b: monthly total rainfall (**a**) and average temperatures (**b**) for the 2010-2011 growing season and the 30-year average. Bar graph shows total monthly rainfall for 2010-11 growing season (horizontally-lined bars) and 30-year average (solid bars). Line graph shows average monthly temperature for 2010-2011 growing season (solid line) and 30-year average (dashed line). Data from the Sutton Bonington met station. 30-year temperature calculated as an average of the average maximum temperature and the average minimum temperature.

2.4.1.2 Field experiment: 2011-12

Three cultivars, Cordiale, Grafton and Xi19, from the previous year's experiment were selected for this year based on current use (all three were in HGCA'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 the yields and digestibilities. The field experiment investigated the effects of chlormequat application and N fertiliser application level. The PGR treatments matched those of the previous field experiment (two-splits of chlormequat). 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 purpose of the N treatments was to see if varying N application rate influenced straw yields and digestibility and, if increasing N rate increases straw yields, does the extra income from the additional straw outweigh the extra variable costs incurred from the extra N.

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. The plots were 24 m by 1.6 m with a gap of 0.5 m between plots. A field experiment plan and a schedule of inputs and management practices used are given in **Appendices 3 and 4**, respectively. The experiment was drilled on the 6^{th} October 2011 (approximately the same time as the previous two field experiments). Standard practices for fertilisers (other than N) and pesticides (other than PGRs) were used.

Rainfall was low at the start of 2012, but other than May, monthly rainfall was far higher than average rainfall (**Fig. 2.2**). Due to the high rainfall during June and July, the plants developed considerable fungal disease. High levels of Fusarium Head Blight (FHB) were observed as well as other fungal diseases including eyespot.

a

b

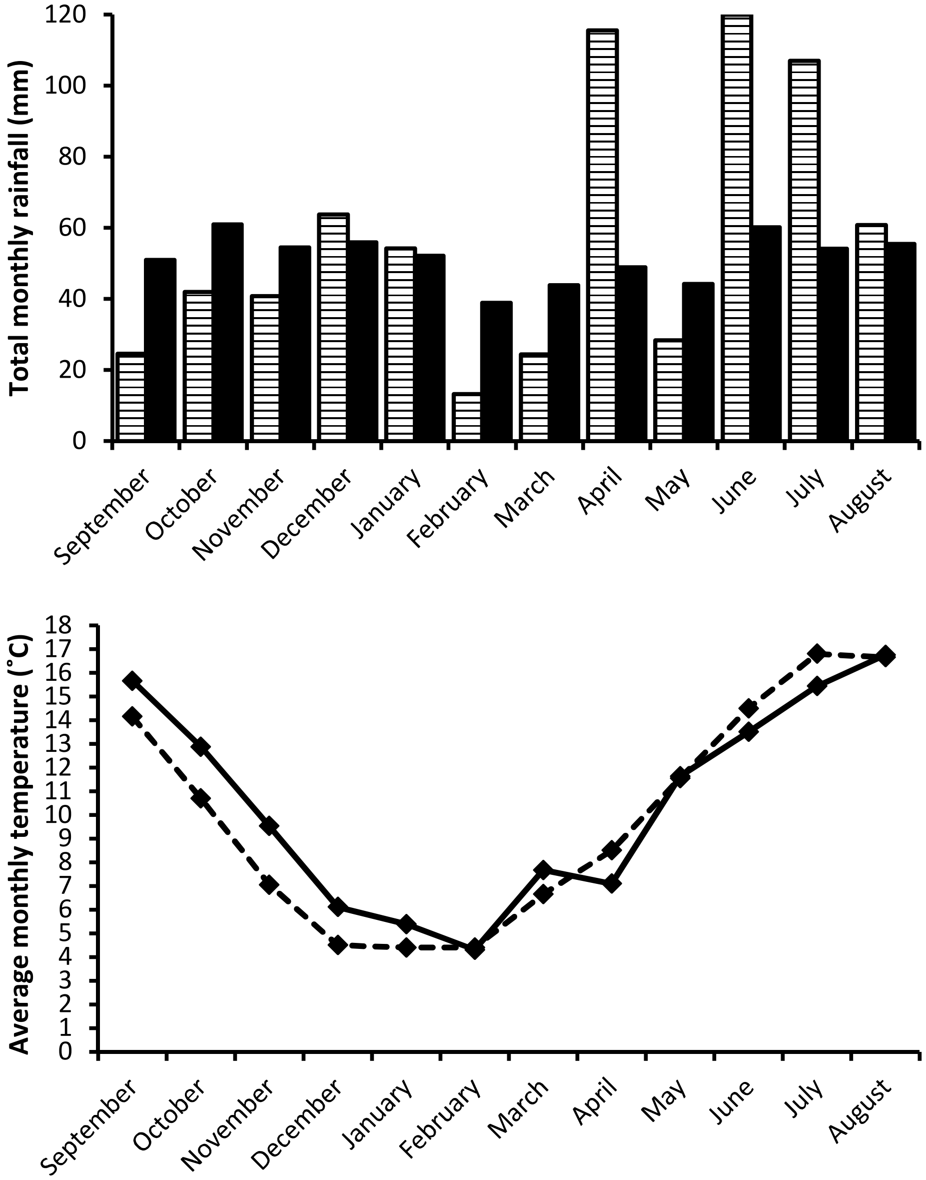


Figure 2.3a, b: monthly total rainfall (**a**) and average temperatures (**b**) for the 2011-2012 growing season and the 30-year average. Bar graph shows total monthly rainfall for 2011-12 growing season (horizontally-lined bars) and 30-year average (solid bars). Line graph shows average monthly temperature for 2011-2012 growing season (solid line) and 30-year average (dashed line). Data from the Sutton Bonington met station. 30-year temperature calculated as an average of the average maximum temperature and the average minimum temperature.

2.4.2 Biomass measurements

2.4.2.1 2011 Stem analysis

Due to the small plot size, a baler could not be used to collect material for each plot and collecting plant material by hand after combining was also not possible as the plots were narrow and there was crossover of material between plots. Therefore, plant material was collected by hand prior to combining. All plants from within a 50 x 50 cm quadrat were collected. To account for the proportion of stem than would be left as stubble on the field, the stem was divided into two parts: the first 10 cm from the ground level and the remainder. This was done with the leaf blades still attached.

This material was placed into paper bags and oven dried at 80°C to constant weight. All weights were converted into tonnes per hectare at 0% moisture content (MC).

2.4.2.2 2012 GS61 analysis

Tiller and plant number were counted at GS61 (growth stages use the decimal system described in Zadoks et al., 1974, and Tottman & Broad, 1987). All the plants within a 50 x 50 cm quadrat were collected. The numbers of plants were counted and then ten plants were randomly selected for counting the number of tillers (including the main stem).

2.4.2.3 2012 Pre-harvest biomass partitioning

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 waterproof 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 ear length was measured because in the previous two field experiments, plant height was measured to the tip of the ears and straw length was not measured. Measuring ear lengths, therefore, allowed stem lengths for the previous field experiments to be estimated.

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% MC, with weights converted to tonnes per hectare. The quadrat sample weights were used for calculating total biomass and harvest indices.

Grain yields from the section of the plot that had yet to be sampled were determined using a plot combine harvester. The yields were corrected to 0% MC based on several moisture measurements taken throughout the plots.

2.4.3 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.

2.4.4 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.

Xi19 was used to compare the digestibility of the different components of the plant. For each plot, 20 stems were randomly selected from the remaining sample; the ears were removed followed by the roots at soil level. These plants were split into the leaf blades, the peduncle, the bottom 10 cm of stem, and the remaining stem (including the leaf sheath, which was left attached due to the difficulty of separating these from the stem). The plant material was cut into sections of 1 cm in length and milled in a centrifugal mill using a 0.5 mm sieve. These samples were stored in sealed plastic bags until the digestion assays were conducted.

The second set of measurements was for a comparison of plant components of Cordiale and Grafton. These measurements only included the N2 treatments. As with Xi19, 20 plants were used but these were split into leaf blades and the stem minus the lower 10 cm portion (but including the peduncle). These were prepared in the same way as the Xi19 samples.

As the assays conducted for the two previous years used the whole plant (less the ear), it was decided to compare whole plant samples for the three cultivars as this allowed a comparison with the previous years. These samples were prepared in the same way as the previous samples.

In all assays, the total glucose present and the amount released after pretreatment were assessed. For the Xi19 samples, the rate of release was compared between treatments. The proportion of total sugars released after 4 hours was compared to the sugars released after 72 hours for the treatments. This analysis was then repeated looking at the proportion of sugars released after 24 hours.

2.4.5 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.

2.5 Results

2.5.1 Biomass assessments

2.5.1.1 GS61 analysis

At GS61, there were no significant differences in plant number between the treatments. Tiller number was very close to being significantly lower for Xi19 than the other two cultivars (*P* = 0.053). PGR and N did not have a significant influence. When tiller number was multiplied by plant number, Xi19 had significantly fewer stems per m^2 than Cordiale or Grafton (*P* <0.001).

2.5.1.2 Grain yields

Grain yield was quantified using both quadrat and combine harvests. Both methods showed high variability. The quadrat samples differed from the combine-collected samples with the quadrat harvest yields ranging from 3.61 t ha^{-1} less than the combine results to 2.05 t ha^{-1} higher. In general the combine harvester collected significantly more grain than quadrat samples (*P* <0.001; an average of 8.42 t ha^{-1} compared to 7.67 t ha^{-1}). There were significant interactions between harvesting method and PGR (*P* = 0.025) where grain yields for the chlormequat-treated plots were higher for quadrat samples but lower for combine samples, and between harvesting method and cultivar (*P* = 0.028) where grain yields were higher in combine-collected samples for the three cultivars but the difference was much larger for Xi19 than the other cultivars. It would be expected that quadrat sampling would have higher yields due to a higher grain recovery rate so it is unclear why the combine yields are higher.

The quadrat samples scored much higher coefficient of variation (CV) with a value of 14.2% for the comparison of the cultivars compared to a value of 6.6% for the combine sample. The quadrat samples (0.25 m^2) were much smaller than those for the combine (16.5 m^2) and the positioning of the quadrat could have had an influence on the number of plants collected, for example if the quadrat happened to be where there was patchy establishment. This goes some way to explaining the greater variability in the data.

Both quadrat (**Fig. 2.4a**) and combine (**Fig. 2.4b**) grain yields were significantly influenced by cultivar (**Table 2.2**). Xi19 was significantly lower than Cordiale and Grafton for both quadrat (P <0.001) and combine (P <0.001). The quadrat grain yield also increased with PGR application (P = 0.040) but the combine grain yield did not.

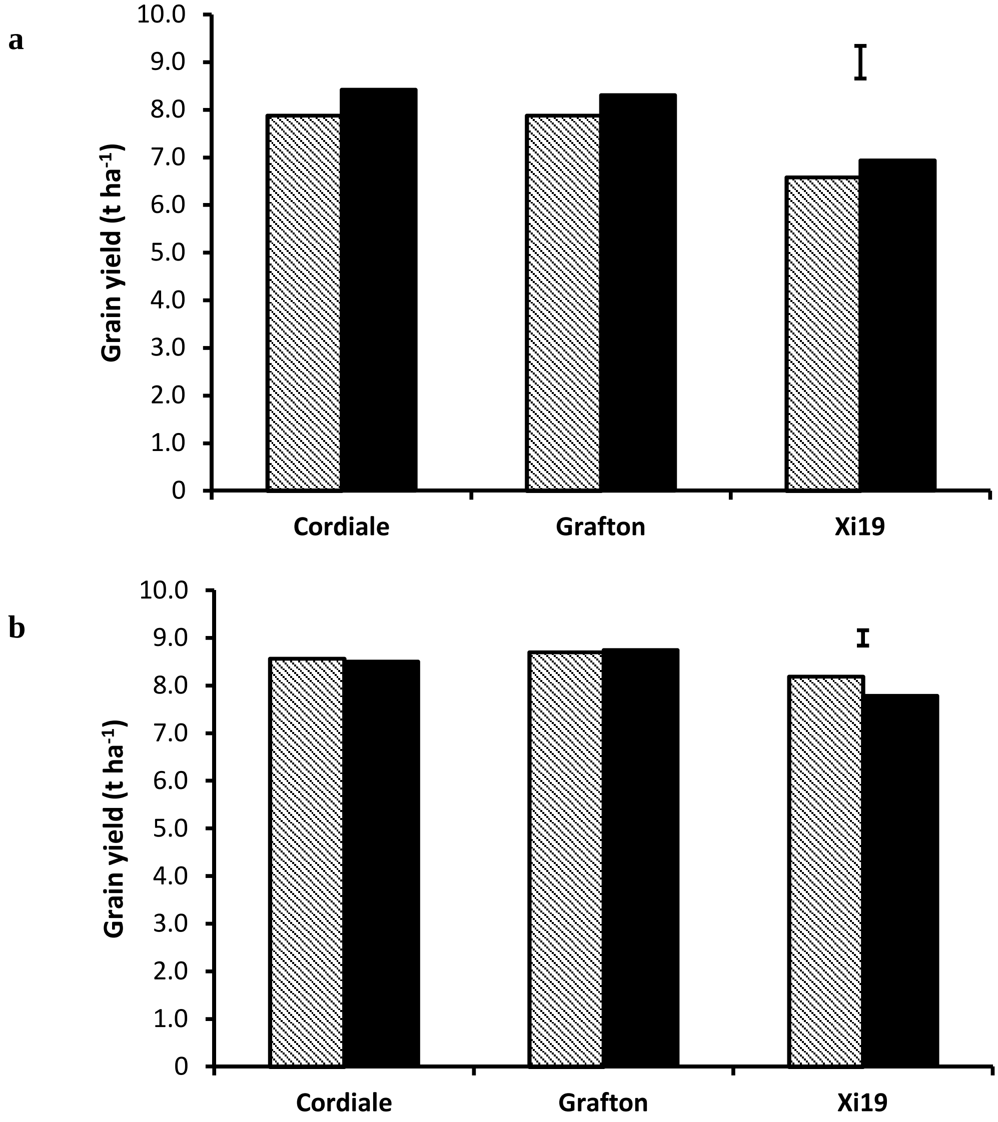


Figure 2.4a, b: Grain yields for quadrat (**a**) and combine harvest (**b**) for the three cultivars and PGR treatments. PGR: untreated (diagonally-lined bars); treated (solid bars). Error bars show S.E.D for the cultivar-PGR interaction.

Table 2.2: Grain yield data and statistics. Quadrat data collected by hand, combine data from the combine harvested plot.

Treatment		**Quadrat grain ($t\ ha^{-1}$)**	**Combine grain ($t\ ha^{-1}$)**
Cultivar	Cordiale	8.15	8.54
	Grafton	8.10	8.72
	Xi19	6.76	7.99
PGR	Without	7.45	8.49
	With	7.89	8.34
N	N1	7.73	8.46
	N2	7.51	8.40
	N3	7.76	8.39
Cultivar	P	<0.001	<0.001
(d.f. = 24)	SED	0.256	0.110
PGR	P	0.040	0.198
(d.f. = 6)	SED	0.169	0.100
N	P	0.887	0.861
(d.f. = 4)	SED	0.559	0.133

2.5.1.3 Straw yields

The four stem sections differed in how they responded to the treatments (**Table 2.3**). 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.

The data allows an assessment of the influence that combine header height might have on straw yields (**Fig. 2.5**). 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 (**Table 2.3**). 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.

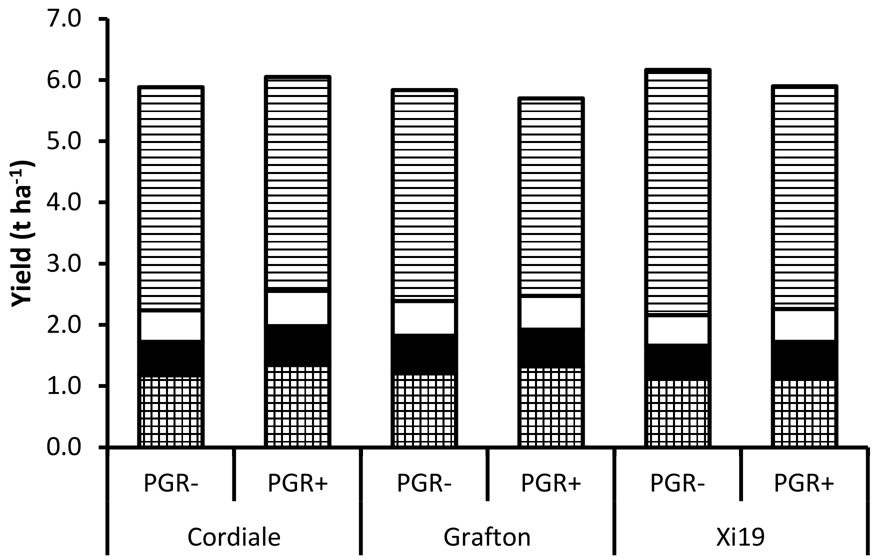


Figure 2.5: Header height and straw yields. S1 (checked bars); S2 (white bars); S3 (solid bars); S4 (horizontally-lined bars). SEDs for the cultivar-PGR interaction are 0.064 (S1), 0.047 (S2), 0.038 (S3) and 0.147 (S4).

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.

When total stem and leaves are combined (total stem plus leaf; **Table 2.3**), no treatments had an 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).

In the assessment of the lower stem weight (lower 10 cm) between the 15 cultivars in the 2010-2011 field experiment there were significant differences in cultivars (*P* = 0.014; **Table 2.4**), with average values ranging from 0.76 to 1.02 t ha^{-1}. However, only Cordiale with the lowest mean weight, and Maris Widgeon, with the highest mean weight, were actually significantly different, with the intermediate values not significantly different from either. PGR application did not significantly influence yields, though there was general trend for higher values without the application of chlormequat. Unlike with the experiment in 2011-2012, the value for the lower 10 cm was reduced with the application of chlormequat; however, a direct comparison is not possible as leaf blade was included in the sample in 2011. There were significant differences between cultivars for the upper stem (*P* <0.001) and total stem (*P* <0.001); however, for both the difference was between Maris Widgeon and the other cultivars (**Table 2.4**).

Table 2.3: Treatment means and key statistical results for the different straw and grain components of the wheat plants. S1 to S4 refer to stem sections: S1 is the lower 10 cm, S2 = 10 cm to 15 cm from the base, S3 = 15 cm to 20 cm from the base, and S4 is the remaining stem. Upper stem is the stem weight minus S1.

Treatment		S1 ($t\ ha^{-1}$)	S2 ($t\ ha^{-1}$)	S3 ($t\ ha^{-1}$)	S4 ($t\ ha^{-1}$)	Total stem ($t\ ha^{-1}$)	Upper stem ($t\ ha^{-1}$)	Stem + leaf ($t\ ha^{-1}$)	Leaf ($t\ ha^{-1}$)
Cultivar	Cordiale	1.26	0.59	0.55	3.57	5.97	4.71	7.77	1.8
	Grafton	1.27	0.6	0.56	3.33	5.77	4.5	7.78	2.02
	Xi19	1.13	0.56	0.52	3.82	6.03	4.9	7.74	1.71
PGR	Without	1.18	0.56	0.53	3.7	5.96	4.79	7.82	1.86
	With	1.27	0.61	0.56	3.45	5.88	4.62	7.71	1.82
N	N1	1.2	0.58	0.53	3.4	5.71	4.51	7.59	1.88
	N2	1.25	0.6	0.56	3.75	6.16	4.91	8.05	1.89
	N3	1.21	0.57	0.54	3.58	5.9	4.69	7.66	1.76
Cultivar	P	0.011	0.317	0.227	0.001	0.327	0.036	0.984	<0.001
(d.f. = 24)	SED	0.047	0.029	0.024	0.114	0.181	0.146	0.232	0.06
PGR	P	0.036	0.202	0.298	0.009	0.566	0.154	0.573	0.639
(d.f. = 6)	SED	0.035	0.033	0.026	0.066	0.134	0.107	0.197	0.073
N	P	0.036	0.272	0.268	0.205	0.133	0.155	0.128	0.034
(d.f. = 4)	SED	0.013	0.017	0.017	0.158	0.17	0.16	0.185	0.035

Table 2.4: Treatment means and statistical analyses for stem sections for treatments in 2010-2011 field experiments. Lower refers to the lower 10 cm of stem and leaf and upper refers to the remaining stem and leaf material that remains after the lower section is removed.

Treatment		**Lower (t ha^{-1})**	**Upper (t ha^{-1})**	**Total (t ha^{-1})**
Cultivar	Ambrosia	0.960	4.462	5.603
	Battalion	0.936	4.202	5.138
	Cordiale	0.764	3.706	4.470
	Glasgow	0.979	4.251	5.230
	Grafton	0.922	3.772	4.694
	Hereward	0.929	4.639	5.568
	Invicta	0.926	4.634	5.560
	Istabraq	0.964	4.824	5.788
	M. Widgeon	1.022	6.413	7.434
	Mascot	0.924	4.537	5.461
	Quartz	0.887	3.714	4.602
	Riband	0.859	4.085	4.944
	Sterling	0.775	3.699	4.474
	Xi19	0.955	4.039	4.994
	Zebedee	0.820	4.269	5.088
PGR	Without	0.926	4.639	5.565
	With	0.891	4.084	4.975
Cultivar	P	0.014	<0.001	<0.001
(d.f. = 56)	S.E.D	0.0692	0.3729	0.4317
PGR	P	0.266	0.156	0.161
(d.f. = 2)	S.E.D	0.0228	0.2489	0.2701

The straw yields for the three cultivars (N2 for 2011-2012 field experiment data, without chlormequat application; blocking structure: year/block) were compared to the yields in 2011 and 2010. There were significant differences in the yields between years (P = 0.002) but not between cultivars (P = 0.063; **Fig. 2.6**). The straw yields were much higher in 2012 than the previous two years, which were similar in their yields. There was a strong non-significant trend of Xi19 having the highest straw yields and Grafton having the lowest straw yields.

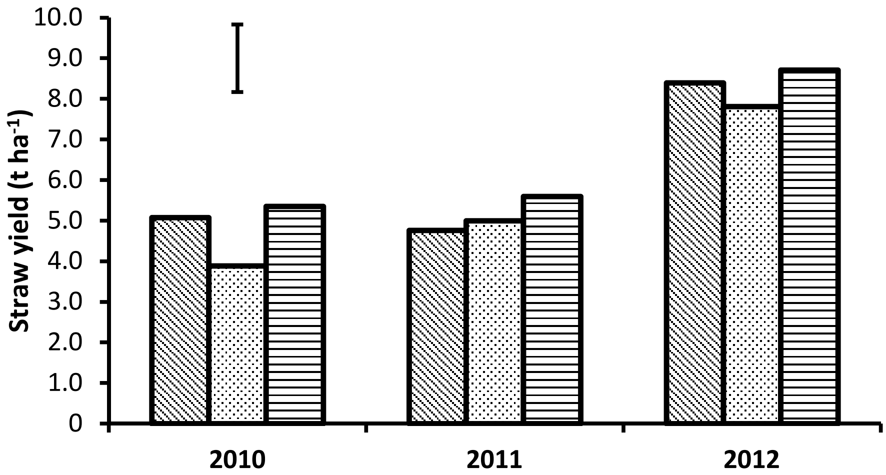


Figure 2.6: Straw yields (combined stem and leaf) for the three cultivars across the three years. Cultivars: Cordiale (diagonal bars); Grafton (dots); and Xi19 (horizontal bars). Error bar shows SED for the cultivar-year interaction.

The straw yields (including leaf sheaths and blades) for 2011 and 2012 were compared with and without PGR application (N2 for 2011-2012 field experiment data; blocking structure: year/block/PGR; **Fig. 2.7**). Straw yields were significantly higher in 2012 (P <0.001). Cultivar did not have a significant influence and neither did PGR; however, there was a trend for PGRs to reduce straw yield.

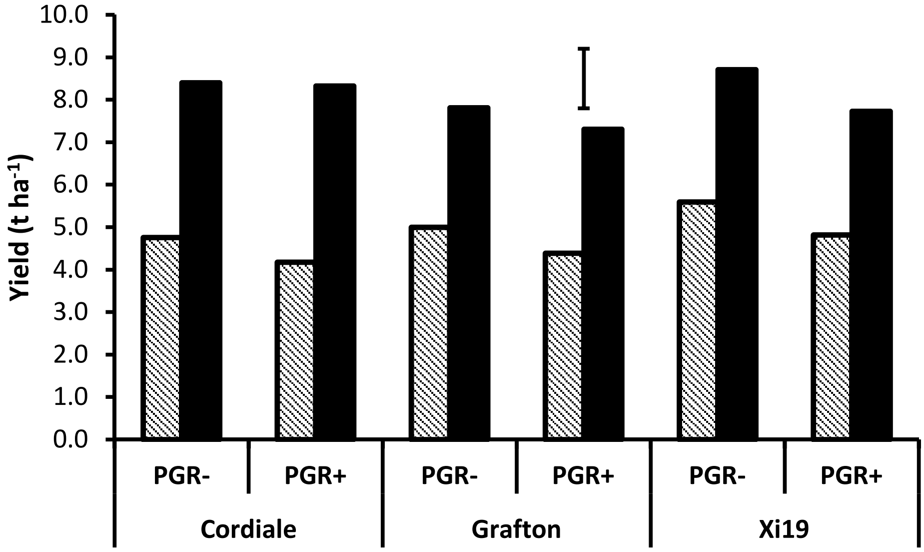


Figure 2.7: Straw yields (stem and leaf) for the cultivars and PGR treatments for two years. Year: 2011 (diagonally-lined bars); 2012 (solid bars). Error bar shows SED for the cultivar-PGR-year interaction.

2.5.1.4 Plant heights

There was a significant difference in stem length between cultivars with straw length of Grafton being significantly shorter than Cordiale, which in turn was significantly shorter than Xi19 (P <0.001). The application of PGRs reduced stem length (P <0.001; **Fig. 2.8**) but N did not have a significant effect. There was a significant interaction between PGR and cultivar (P = 0.007) with a much greater reduction in height for Xi19 than Cordiale and Grafton when PGRs were applied.

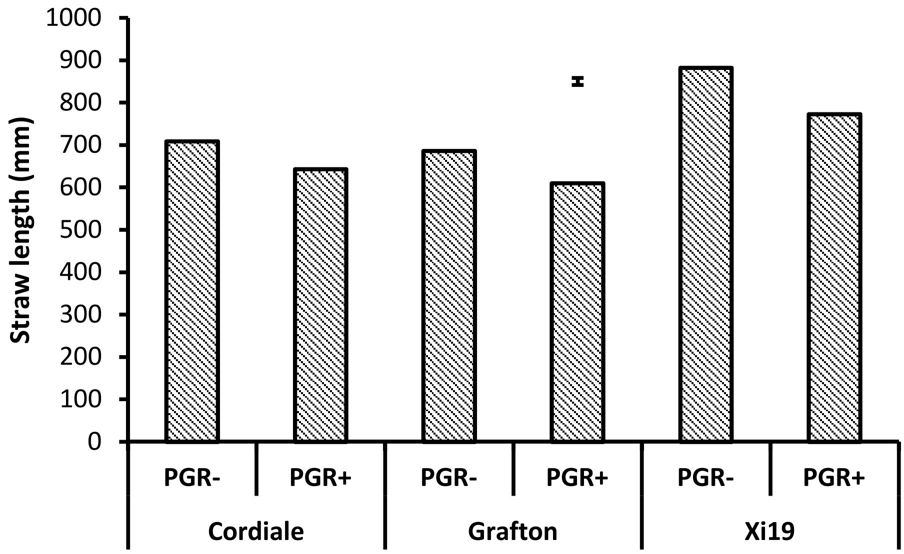


Figure 2.8: Effects of cultivars and PGR application on stem length. Stem lengths for the cultivars and PGR treatments. Error bar shows SED for cultivar-PGR interaction.

Spike length varied with cultivar (*P* <0.001) with Xi19 having a significantly longer spike than Grafton or Cordiale. Neither PGR nor N influenced spike length. This indicates that when using plant height as a proxy for stem length, there is a possibility that there is a small loss of accuracy.

The spike lengths were used to correct the plant heights from the previous two field experiments to allow a comparison of stem lengths between years. The stem lengths for the three cultivars were compared between the three years (N2 for 2011-2012 field experiment data, without chlormequat; blocking structure: year/block). Stem length also significantly differed between the three cultivars (*P* < 0.001), with Xi19 being significantly taller than Cordiale, which in turn was significantly taller than Grafton (**Fig. 2.9**). Stem length significantly differed between the three years (*P* <0.001) with the shortest plants in 2010 and the tallest plants in 2012. However, there was a significant interaction between year and cultivar (P = 0.004), which was due to Xi19 not being taller in 2011 than 2010.

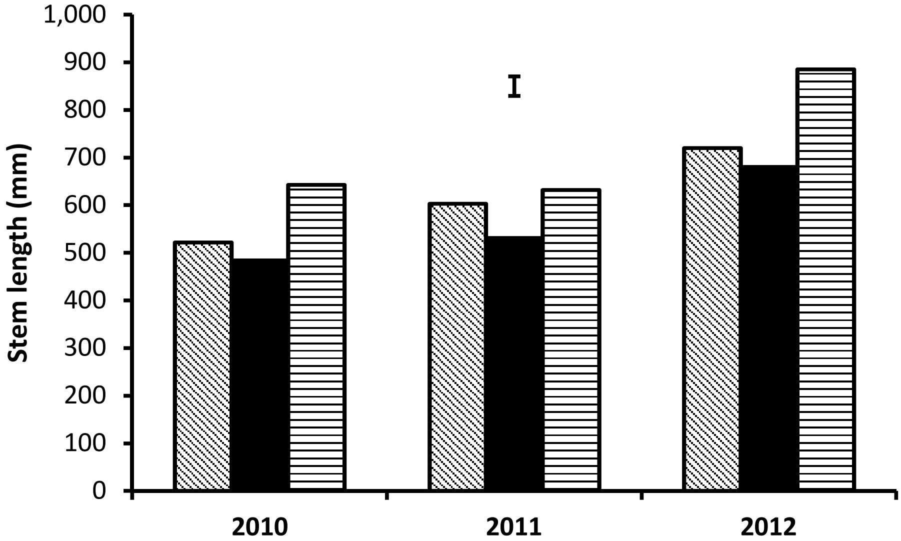


Figure 2.9: Stem lengths for the cultivars for the three years (N2, no PGR)**.** Cultivars: Cordiale (diagonally-lined bars); Grafton (solid bars); and Xi19 (horizontally-lined bars). Error bar shows SED for the cultivar-PGR interaction.

Stem lengths in 2011 and 2012 were compared to look at PGR treatments (N2 for 2011-2012 field experiment data; blocking structure: year/block/PGR). Stem lengths were shorter in 2011 than 2012 (P <0.001; **Fig. 2.10**), all three cultivars significantly differed following the height pattern given above (P <0.001), and PGR shortened stems (P <0.001). There was a significant interaction between year and cultivar (P <0.001) with a much larger difference in height between years for Xi19 than the other cultivars.

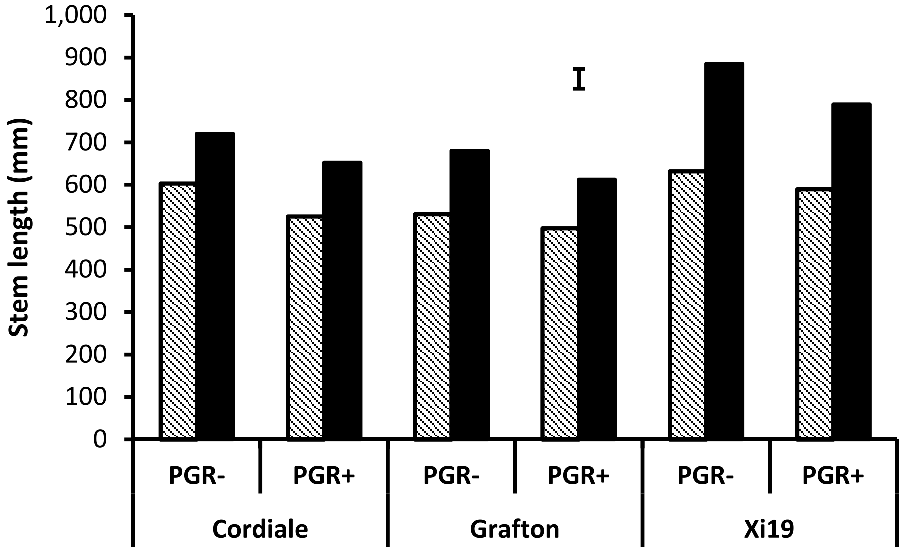


Figure 2.10: Stem lengths for the cultivars for 2011 and 2012 with and without PGRs. 2011 samples (diagonally-lined bars); 2012 samples (solid bars). Error bar shows SED for the cultivar-PGR-year interaction.

Stem density was calculated for the samples as stem yield per hectare divided by stem length. This is an unconventional measurement but stem number was not counted at harvest meaning that it was not possible to calculate stem density as weight per stem divided by stem length. Grafton and Cordiale had significantly greater stem density than Xi19 (P <0.001) and PGR significantly increased stem density (P = 0.004; **Fig. 11**). N did not significantly influence stem density. Therefore, these results suggest that even though stem length differed significantly between treatments, the lack of significant total straw yield differences was a result of shorter cultivars having denser straw. This data does not support that there is a direct relationship between straw height and yield when comparing cultivars and chlormequat application. However, the difference between cultivars might in part be explained by plant number and tiller number; at GS61 Xi19 had a lower stem number. If the stem number from GS61 is used, the stem density (as mg mm^{-1}) does not significantly differ between cultivars or N treatment, though there is a non-significant trend for higher stem density with chlormequat application ($P = 0.055$).

For the samples from 2011, stem density could not be calculated directly as samples included leaf material as well. Instead, they were calculated as total straw and leaf yield divided by plant height (to the tip of ear) for each replicate. There were no significant differences between cultivars or differences with PGR application. This suggests that there is a relationship between straw length and yield, and that PGR does not increase straw density, which conflicts with the results for 2012. As different biomass measurements were used, the stem density of 2012 samples was recalculated using total straw and leaf yield and height to the tip of the ear. However, the significance of PGR and cultivar are maintained, suggesting the difference between years is not just a result of different height and biomass measurements being used, and reflects a difference in the growth of the plants between years.

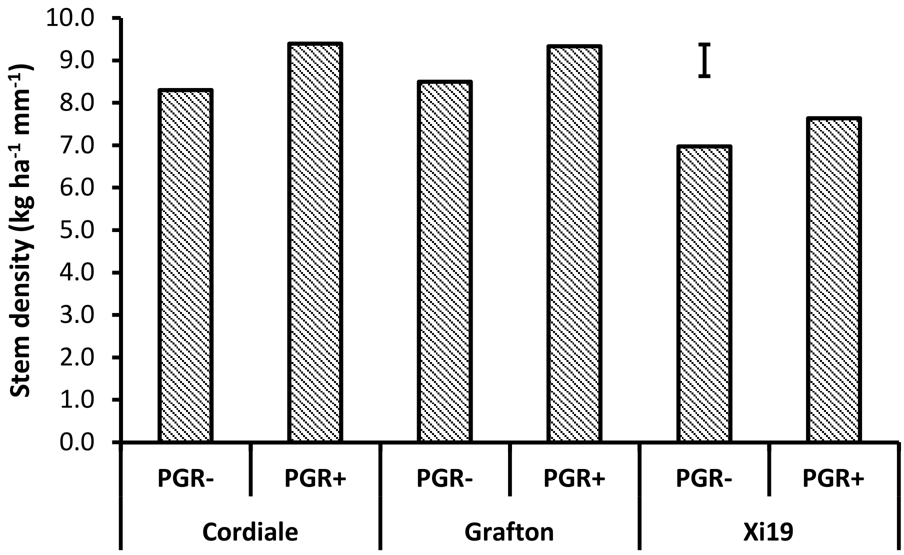


Figure 2.11: Stem density for the cultivars in 2012 with and without PGRs. Stem density is the total stem weight per hectare divided by average stem height for that plot. Error bar shows SED for the cultivar-PGR interaction.

2.5.1.5 Straw and grain relationship

Xi19 had significantly lower total biomass than Cordiale and Grafton (*P* = 0.017; **Table 2.5**; **Fig. 2.12a**). 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; **Table 2.5**; **Fig. 2.12b**) 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).

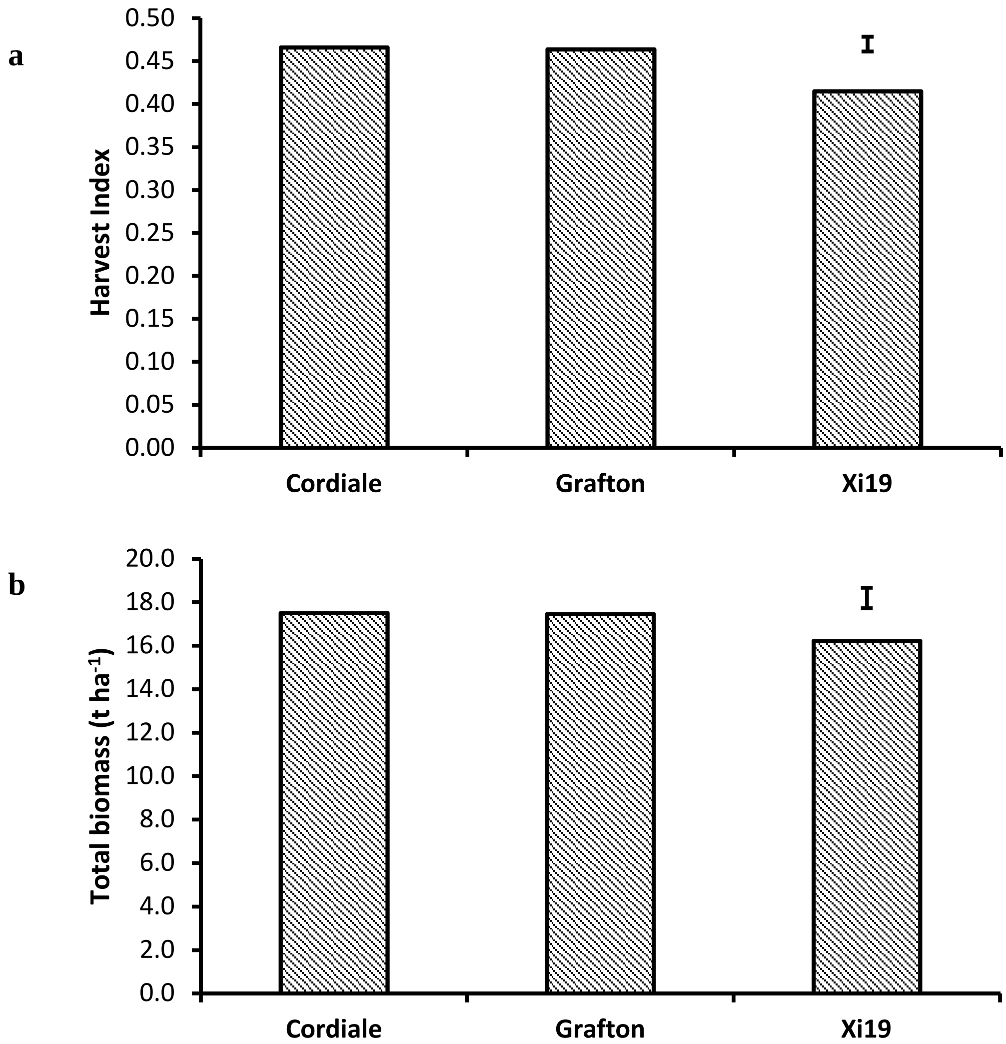


Figure 2.12a, b: Total biomass for cultivars (**a);** harvest indices for cultivars (**b)**. Error bars show SED for the cultivar-PGR interaction.

The HIs were compared to those from 2011 and 2010 (N2 level without chlormequat application; **Fig. 2.13**). HI was significantly lower in 2012 than in the previous two years (*P* <0.001) and Xi19 had significantly lower HI than the other two cultivars (*P* = 0.013).

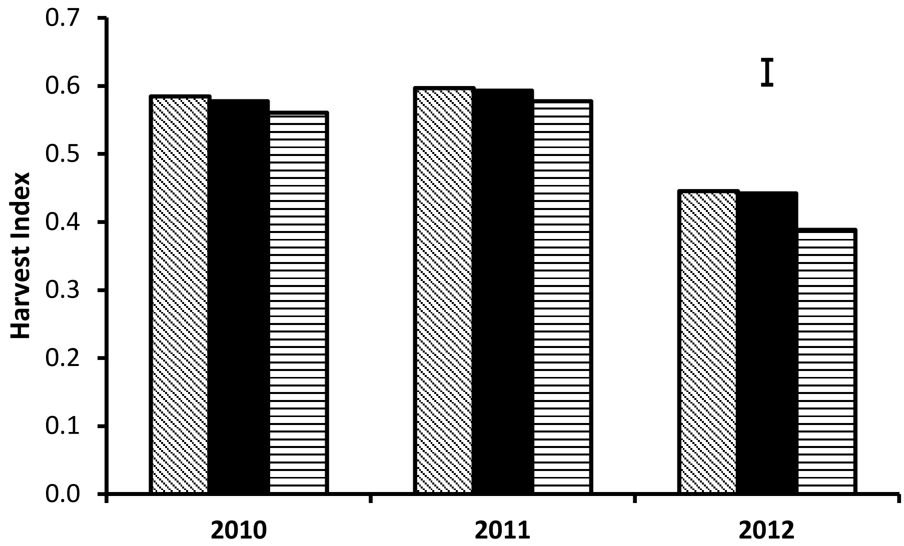


Figure 2.13: The effects of cultivar and year on harvest indices. Data for non-chlormequat treated samples. Cultivars: Cordiale (diagonally-lined bars); Grafton (solid bars); Xi19 (horizontally-lined bars). Error bar shows SED for the cultivar-year interaction.

When the values for 2011 and 2012 were compared (N2 treatment) with the PGR treatments, there was a significant interaction between cultivar and year (P = 0.013; **Fig. 2.14**) where in 2011 the three cultivars did not significantly differ but in 2012 Xi19 had a significantly lower HI than Cordiale and Grafton. PGR significantly increased HI (P = 0.003). HI was much lower in 2012 due to straw yields being considerably higher than the previous two years whilst grain yields were similar.

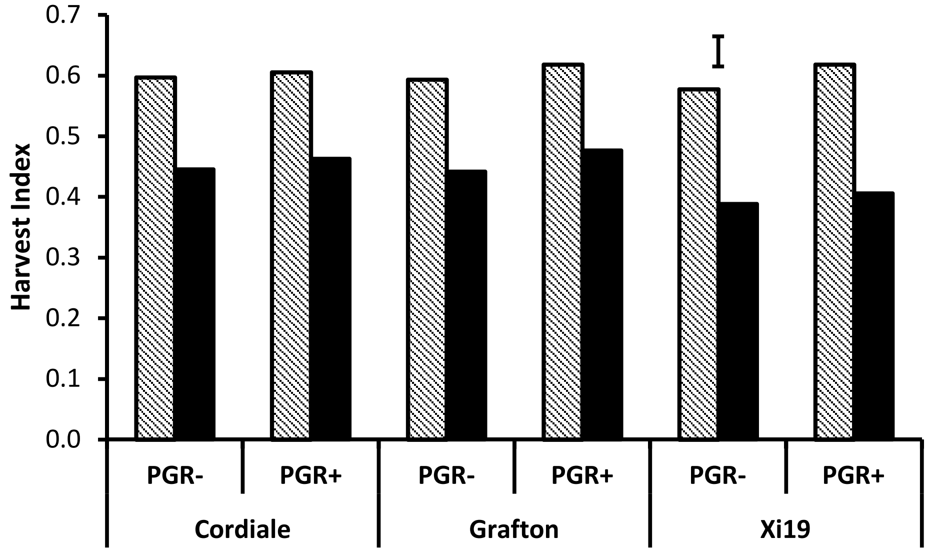


Figure 2.14: The effect of cultivar, PGR and year on harvest indices. Years: 2011 (diagonally-lined bars); 2012 (solid bars). Error bar shows SED for cultivar-PGR-year interaction.

When considering variability, total straw yield for all plots had a lower CV (10.49%) than quadrat grain (14.15%) but higher than combine-collected grain yield (6.6%). The high CV for quadrat grain is due to the greater variability in grain yields of Xi19 (CV of 16.0% compared to 9.7% and 9.2% for Cordiale and Grafton, respectively).

When the CV of average total straw yields (without PGR) and quadrat-grain yields (without PGR) of the three years are compared for each cultivar there is a higher CV for straw than for grain. Cordiale and Grafton are similar with variation of 13.85% and 11.88%, respectively, for grain and 30.83% and 33.16%, respectively, for straw. The variation in results for Xi19 differs with values for grain, 22.80%, and straw, 25.90%, being much more similar. It is unclear why the grain yield was so variable for Xi19.

Table 2.5: Total biomass and harvest indices for treatments.

Treatment		Total biomass ($t\ ha^{-1}$)	Harvest index
Cultivar	Cordiale	17.51	0.47
	Grafton	17.46	0.46
	Xi19	16.22	0.42
PGR	Without	16.82	0.44
	With	17.30	0.45
N	N1	16.98	0.46
	N2	17.11	0.44
	N3	17.09	0.45
Cultivar	P	0.017	<0.001
(d.f. = 24)	SED	0.467	0.009
PGR	P	0.168	0.090
(d.f. = 6)	SED	0.309	0.006
N	P	0.957	0.698
(d.f. = 4)	SED	0.491	0.022

2.5.2 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.

2.5.2.1 Failure wind speeds

SFWS was lower than RFWS for all plots indicating that the plants were more likely to stem lodge than root lodge (**Table 2.6**). Xi19 had a significantly lower SFWS than Cordiale and Grafton (*P* <0.001). PGRs increased the SFWS (*P* =

0.001; **Fig. 2.15**) 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.

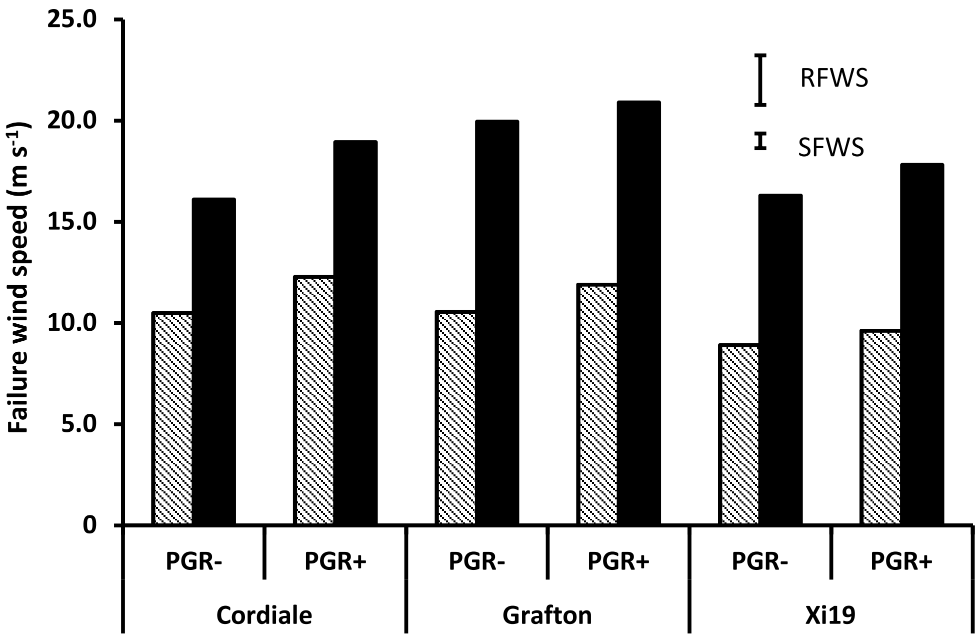


Figure 2.15: Stem and root failure wind speeds for cultivars and PGR treatments. Failure wind speed: SFWS (diagonally-lined bars); RFWS (solid bars). Error bars show SED for the cultivar-PGR interaction with label referring to the corresponding data.

Table 2.6: Treatment means and key statistics results for root and stem failure wind speeds.

Treatment		SFWS (m s^{-1})	RFWS (m s^{-1})
Cultivar	Cordiale	11.38	17.52
	Grafton	11.22	20.43
	Xi19	9.26	17.06
PGR	Without	9.98	17.45
	With	11.26	19.22
N	N1	10.88	19.07
	N2	10.72	17.33
	N3	10.27	18.60
Cultivar	P	<0.001	<0.001
(d.f. = 24)	SED	0.255	0.737
PGR	P	0.001	0.092
(d.f. = 6)	SED	0.217	0.884
N	P	0.263	0.718
(d.f. = 4)	SED	0.328	2.125

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 internode 1 and internode 2 were significantly lower for Xi19 than the other cultivars (*P* <0.001 for both; **Table 2.7**); it was 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).

Table 2.7: Treatment means and key statistical results for the main components of the lodging model.

Treatment		Internode 1 stem leverage (Nmm)	Internode 2 stem leverage (Nmm)	Internode 1 material strength (MPa)	Internode 2 material strength (MPa)	Leverage on root base (Nmm)	Anchorage strength (Nm)
Cultivar	Cordiale	154	141	41.43	22.09	638	1.136
	Grafton	154	140	29.95	16.31	656	1.614
	Xi19	279	255	30.55	19.78	1038	1.819
PGR	Without	213	195	33.62	19.19	842	1.519
	With	179	163	34.33	19.59	712	1.527
N	N1	183	167	32.41	18.72	726	1.561
	N2	200	182	35.22	19.97	793	1.364
	N3	204	187	34.3	19.48	813	1.644
Cultivar	P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
(d.f. = 24)	SED	7.49	7.17	1.563	0.991	51.3	0.115
PGR	P	0.001	<0.001	0.635	0.571	0.002	0.942
(d.f. = 6)	SED	5.98	5.19	1.426	0.66	25.4	0.107
N	P	0.041	0.035	0.652	0.49	0.311	0.679
(d.f. = 4)	SED	5.52	4.82	2.929	0.965	44.8	0.312

2.5.2.2 Lower internode characteristics

Lower internode characteristics were analysed to understand the variation in material strength for internode 1 (**Table 2.8**) and internode 2 (**Table 2.9**). Only cultivar had a significant influence on any of the characteristics of internode 1, which explains why other treatments did not influence internode 1 material strength. Although PGR and N had an influence on some of the characteristics of internode 2, this was not strong enough to cause a significant difference in the material strength of that internode.

No treatments influenced internode 1 breaking strength. The breaking strength of internode 2 was increased by PGR (P = 0.006) and Cordiale had a significantly lower breaking strength (P = 0.002). N did not have an influence. For internode 1, Xi19 had a significantly larger stem diameter than Grafton, which was in turn significantly larger than Cordiale (P <0.001). For internode 2, Xi19 and Grafton had significantly wider diameters than Cordiale (P <0.001). For internode 1, there was a non-significant trend for Xi19 to be longer than the other cultivars (P = 0.058). For internode 2, Grafton was significantly shorter than the other cultivars (P = <0.001) and PGR significantly lowered internode length (P <0.001). No individual treatments had an influence on the internode 1 wall width though there was a non-significant trend for increased wall width with the application of PGRs (P = 0.079). The interaction between PGR and cultivar was close to significant (P = 0.052) with Xi19 being thinner with the application of chlormequat whilst Grafton and Cordiale were wider. Cultivar had a significant influence on internode 2 wall width (P = 0.002). For both internode 1 and 2 there was a significant interaction between N, PGR and cultivar (P = 0.008 and P = 0.007, respectively). This appears to be because there is a large difference in wall width for Grafton with N2 between the PGR treatments; this is found with both internodes 1 and 2.

Table 2.8: Treatment means and key statistical results for internode 1 characteristics.

Treatment		**Breaking strength (N)**	**Diameter (mm)**	**Length (mm)**	**Wall width (mm)**
Cultivar	Cordiale	16.16	3.38	44.20	1.08
	Grafton	15.01	3.79	44.00	1.09
	Xi19	15.21	4.03	50.30	1.06
PGR	Without	14.68	3.73	47.40	1.06
	With	16.23	3.74	44.90	1.09
N	N1	15.21	3.76	45.30	1.08
	N2	15.43	3.74	48.60	1.07
	N3	15.73	3.70	44.60	1.08
Cultivar	P	0.431	<0.001	0.058	0.459
(d.f. = 24)	S.E.D	0.928	0.069	2.84	0.021
PGR	P	0.161	0.753	0.268	0.079
(d.f. = 6)	S.E.D	0.968	0.026	2.07	0.015
N	P	0.882	0.785	0.355	0.907
(d.f. = 4)	S.E.D	1.013	0.093	2.60	0.042

Table 2.9: Means and key statistical results for internode 2 characteristics.

Treatment		**Breaking strength (N)**	**Diameter (mm)**	**Length (mm)**	**Wall width (mm)**
Cultivar	Cordiale	4.87	3.89	91.19	0.80
	Grafton	5.62	4.28	78.23	0.82
	Xi19	5.82	4.25	90.15	0.87
PGR	Without	4.96	4.14	92.09	0.81
	With	5.91	4.14	80.95	0.85
N	N1	5.40	4.13	85.01	0.84
	N2	5.44	4.17	89.40	0.80
	N3	5.46	4.12	85.15	0.85
Cultivar	P	0.002	<0.001	<0.001	0.002
(d.f. = 24)	S.E.D	0.248	0.048	1.162	0.016
PGR	P	0.006	0.856	<0.001	0.161
(d.f. = 6)	S.E.D	0.231	0.031	0.709	0.022
N	P	0.991	0.085	0.423	0.583
(d.f. = 4)	S.E.D	0.512	0.018	3.402	0.039

2.5.2.3 Stem and ear characteristics

Leverage of internodes 1 and 2 were both influenced by all treatments (**Table 2.10**). The HCG was significantly higher for Xi19 than Cordiale, which in turn was significantly higher than for Grafton (*P* <0.001); it was not influenced by N but was reduced by PGR (*P* <0.001).

Xi19 had a significantly lower natural frequency than Cordiale and Grafton (*P* <0.001) whilst PGR increased natural frequency (*P* <0.001). There was a strong trend for an interaction between cultivar and PGRs (P = 0.074), with the increase in natural frequency resulting from chlormequat application being greater for Cordiale and Grafton than Xi19.

Xi19 had significantly larger ear area and lower ear number than Cordiale and Grafton (P <0.001 and P = 0.007, respectively). PGR did not significantly influence ear number. At GS61 there was a general pattern of higher tiller number with PGR application but it is possible that this higher tillering seen at GS61 did not lead to a greater number of tillers forming ears, hence the lack of a pattern at GS75.

The reason for the significance of N treatments on stem leverage but not on the stem characteristics that make up stem leverage is due to the cumulative effect of non-significant differences. There were non-significant increases in ear area, ear number and HCG, and a non-significant decrease in natural frequency as N application increased; taken together these had a significant impact on stem leverage.

Table 2.10: Treatment means and statistics for key stem characteristics.

Treatment		Ear area (cm^2)	HCG (mm)	Natural frequency (Hz)	Ear number
Cultivar	Cordiale	10.91	510.4	0.94	4.12
	Grafton	11.78	486.5	0.99	4.24
	Xi19	13.93	589.1	0.69	3.71
PGR	Without	12.14	551.9	0.80	4.00
	With	12.27	505.5	0.95	4.04
N	N1	11.85	522.8	0.91	3.95
	N2	12.30	533.7	0.87	4.01
	N3	12.47	529.6	0.85	4.10
Cultivar	P	<0.001	<0.001	<0.001	0.007
(d.f. = 24)	S.E.D	0.208	4.08	0.020	0.157
PGR	P	0.485	<0.001	<0.001	0.722
(d.f. = 6)	S.E.D	0.182	4.32	0.020	0.112
N	P	0.346	0.493	0.183	0.722
(d.f. = 4)	S.E.D	0.382	8.43	0.025	0.174

2.5.2.4 Root traits

Anchorage strength depends on the rooting depth and root plate spread (**Table 2.11**). Cordiale had a significantly smaller root plate spread than the other cultivars (P <0.001) whilst neither PGR nor N had significant effects. Xi19 had significantly shorter rooting depth than the other cultivars (P = 0.002). There was a non-significant trend for an interaction between cultivar and PGR (P = 0.068), which results from Grafton's rooting depth decreasing with the application of chlormequat whilst the rooting depth of Xi19 and Cordiale both increase. Neither PGR nor N had individual effects.

Grafton had the highest RFWS due to having high anchorage strength and low leverage acting on the root base. Xi19 and Cordiale had significantly lower RFWS than Grafton because Xi19 had high anchorage strength but also high leverage whereas Cordiale had low leverage and low anchorage strength.

Table 2.11: Treatment means of root characteristics.

Treatment		**Root plate spread (mm)**	**Root depth (mm)**
Cultivar	Cordiale	36.33	36.72
	Grafton	40.91	36.92
	Xi19	42.36	33.35
PGR	Without	39.63	34.94
	With	40.10	36.39
N	N1	40.12	34.06
	N2	38.50	35.32
	N3	40.98	37.62
Cultivar	P	<0.001	0.002
(d.f. = 24)	S.E.D	0.981	1.005
PGR	P	0.629	0.108
(d.f. = 6)	S.E.D	0.918	0.765
N	P	0.689	0.540
(d.f. = 4)	S.E.D	2.785	3.015

2.5.3 Digestibility assessments

2.5.3.1 Xi19

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. 2.16**), 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.

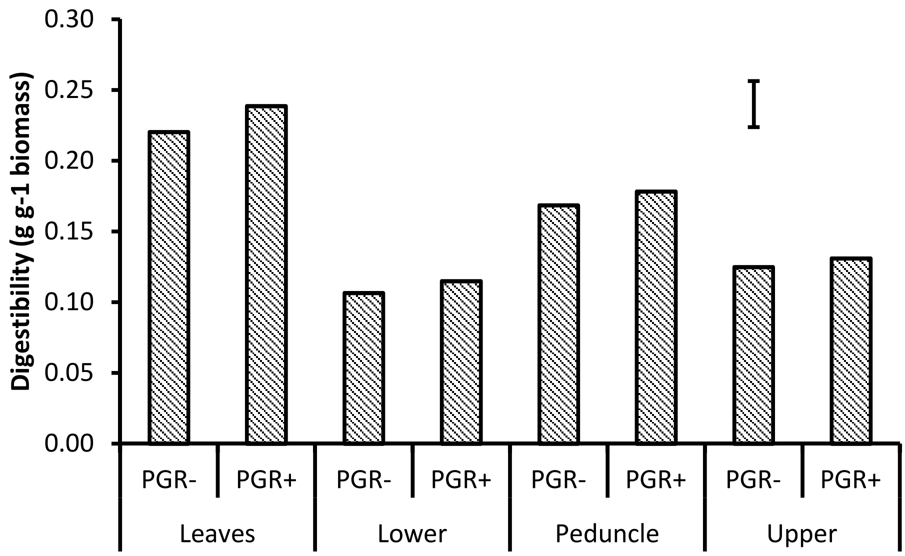


Figure 2.16: Digestibility means for fractions of Xi19 and PGR treatments. Error bar shows SED for the fraction-PGR interaction.

Leaf had significantly less glucose than the other components (*P* <0.001; **Table 2.x**). 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.

Table 2.12: Treatment means and key statistical analysis results for straw digestibility and glucose content of the cultivar Xi19.

Treatment		**Digestibility ($g\ g^{-1}$ biomass)**	**Sugar content ($g\ g^{-1}$ biomass)**
Component	Leaves	0.229	0.443
	Lower	0.111	0.496
	Peduncle	0.173	0.522
	Upper	0.128	0.537
PGR	Without	0.155	0.491
	With	0.166	0.508
Nitrogen	N1	0.165	0.529
	N2	0.163	0.487
	N3	0.153	0.484
Component	P	<0.001	<0.001
(d.f. = 36)	SED	0.0129	0.018
PGR	P	0.049	0.306
(d.f. = 6)	SED	0.0043	0.016
Nitrogen	P	0.207	0.097
(d.f. = 4)	SED	0.00588	0.017

For the rate of glucose release, after 4 hours, N and PGR did not have a significant influence. The peduncle had a slower rate of release compared to the lower stem and leaves, with the upper stem having an intermediate rate of release (P = 0.003). After 24 hours, N and PGR did not have a significant influence on the rate of release. Leaf had a quicker rate of release than the upper stem and the peduncle, with the lower stem having an intermediate rate of release (P = 0.011).

2.5.3.2 Cordiale and Grafton

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. 2.17**; **Table 2.13**), but cultivars did not significantly differ.

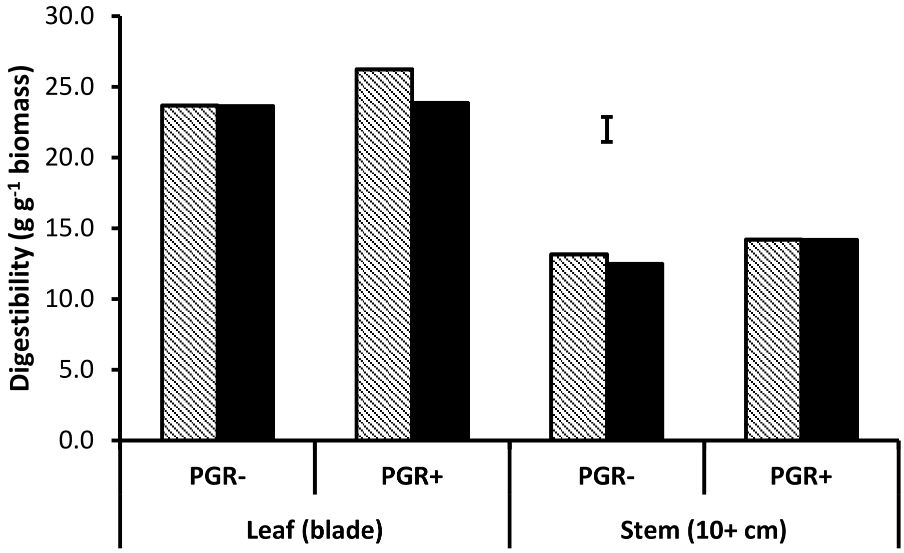


Figure 2.17: The effect of PGR, cultivar and plant fraction on digestibility.

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 but 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.

Table 2.13: Treatment means and key statistical analysis results for straw digestibility and glucose content of the cultivars Cordiale and Grafton.

Treatment		**Digestibility (g g^{-1} biomass)**	**Sugar content (g g^{-1} biomass)**
Component	Leaf	0.244	0.329
	Stem	0.135	0.352
PGR	Without	0.183	0.316
	With	0.196	0.364
Cultivar	Cordiale	0.186	0.337
	Grafton	0.193	0.344
Component	P	<0.001	0.093
(d.f. = 8)	SED	0.0050	0.012
PGR	P	0.023	0.074
(d.f. = 2)	SED	0.0021	0.014
Cultivar	P	0.181	0.628
(d.f. = 4)	SED	0.0048	0.013

2.5.3.3 Whole plant assays

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. 2.18**; blocking structure: block/PGR) but PGRs did not have a significant impact. The reason why the effect of PGR was significant when Xi19 was looked at independently is because the N1 and N3 treatments gave a much larger difference between PGRs treatments than N2. Excluding N1 and N3 from the whole plant analysis meant that this significance is harder to find. The mean values follow the general trend of PGRs increasing digestibility. Leaf-to-stem ratio was not measured for the samples used in the digestibility assays but when using the ratio calculated earlier (**section 2.5.1.3**) the pattern of digestibility of the whole samples does not match that of the leaf-to-stem ratio. However, leaf material was lost between harvest and sampling due to the fragile nature of the leaves, meaning the ratio was likely to be very variable.

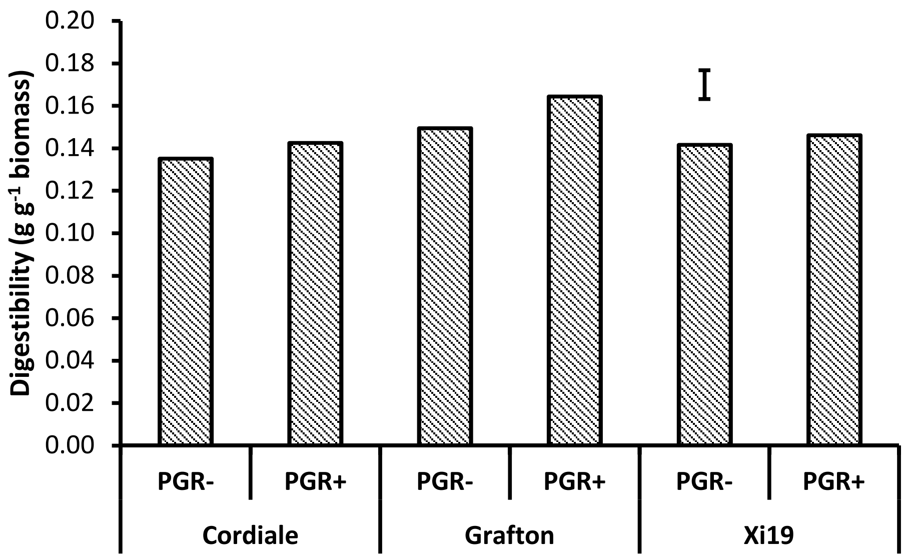


Figure 2.18: Digestibility means for the whole plant samples for the three cultivars. Error bar shows SED for the cultivar-PGR interaction.

Xi19 had approximately 50% more total mass that was glucose than Cordiale and Grafton (P <0.001; **Fig. 2.19**; **Table 2.14**). 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.

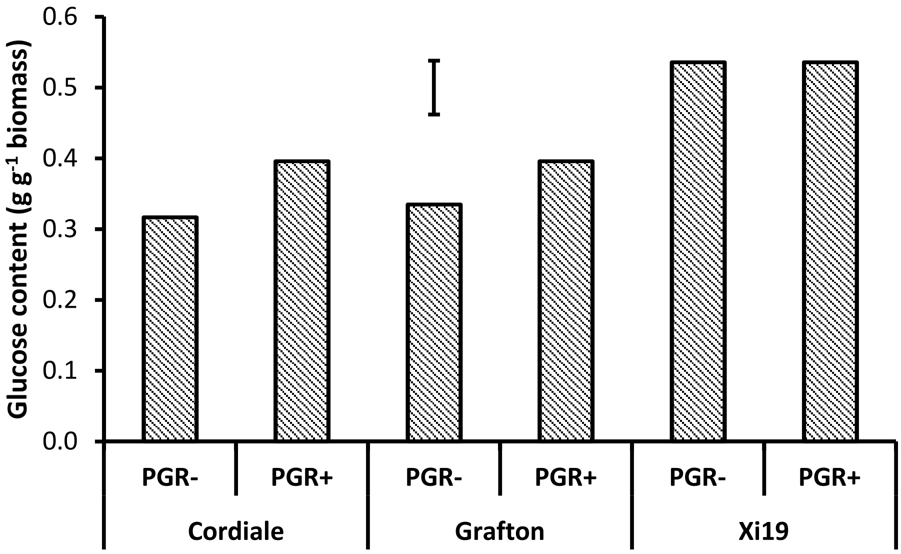


Figure 2.19: Glucose content for whole samples of the three cultivars with and without PGRs. Error bar shows SED for the cultivar-PGR interaction.

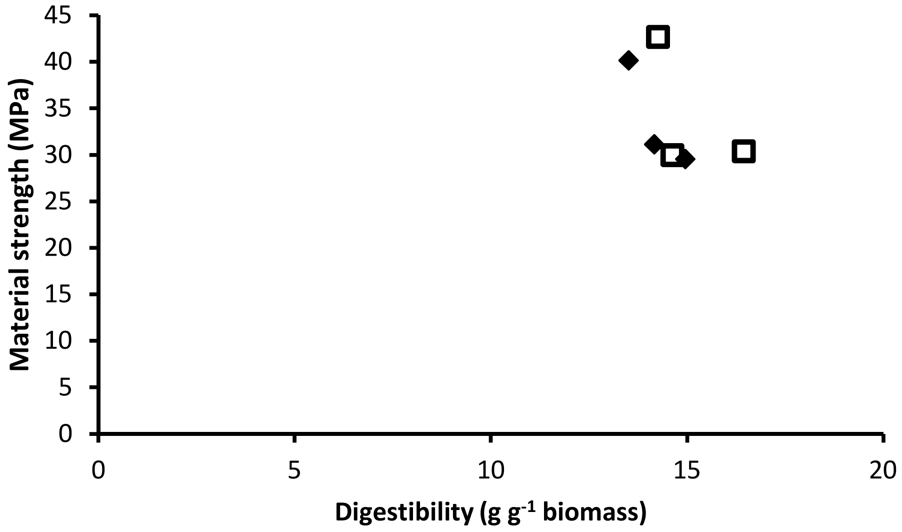
Table 2.14: Treatment means and key statistical analysis results for straw digestibility and glucose content of the whole stem samples of the three cultivars.

Treatment		Digestibility ($g\ g^{-1}$ biomass)	Sugar content ($g\ g^{-1}$ biomass)
Cultivar	Cordiale	0.139	0.357
	Grafton	0.157	0.366
	Xi19	0.144	0.536
PGR	No	0.142	0.396
	Yes	0.151	0.443
Cultivar	P	0.017	<0.001
(d.f. = 8)	SED	0.0049	0.0289
PGR	P	0.142	0.011
(d.f. = 2)	SED	0.0038	0.0490

2.5.4 Material strength and digestibility

Making direct comparisons is difficult because the measurements were taken at different times and for different plants. Because of this mean values are used to compare between the main traits. There was a correlation between the total plant digestibility and material strengths of internodes 1 and 2, for both chlormequat treated and untreated plant material (**Fig. 2.20a, b**). Grafton had the highest digestibility whilst having the lowest material strength (except for internode 1 material strength of chlormequat-treated straw). Cordiale had the lowest digestibility but had the highest material strength of all samples.

a



b

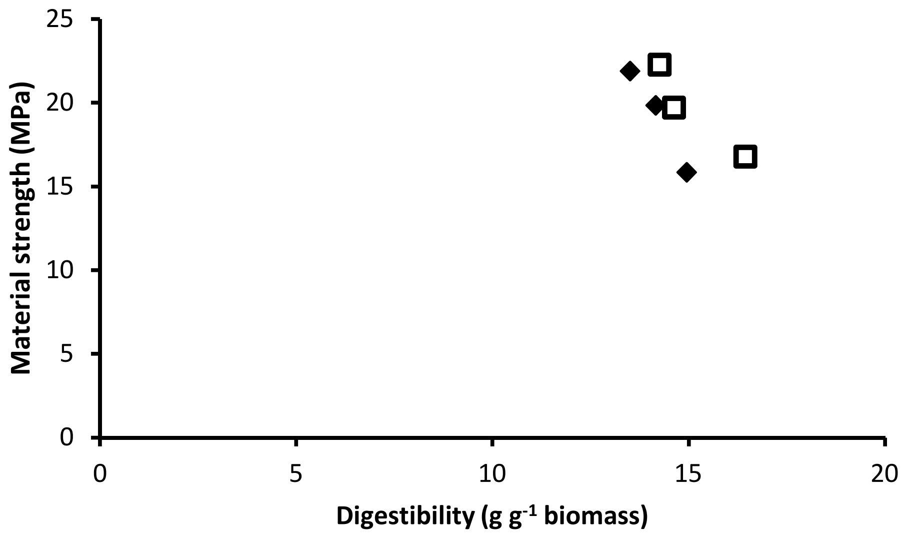


Figure 2.20a, b: Mean digestibility and material strength for internode 1 (**a**) and internode 2 (**b**) for each cultivar with and without chlormequat. PGR treatment: untreated (diamonds); treated (squares).

2.6 Discussion

2.6.1 Biomass assessments

The results of the current investigation taken together with the previous two field experiments (from Roy, 2014) demonstrate the variability in crop 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., 2012b), 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, 2013c). This was in strong contrast to the previous two summers where rainfall was low.

For the 2012 experiments, the cultivars varied in grain yield with Xi19 having a much lower grain yield than Grafton and Cordiale. The average grain yields from the HGCA RLs (15% MC) for Grafton, Cordiale and Xi19 are 10.34, 10.18 and 10.35 t ha^{-1}, respectively. These are similar to the combine-collected (15% MC, with chlormequat) grain samples of Grafton and Cordiale, 10.29 and 10.00 t ha^{-1}, respectively, but higher than Xi19, which had a yield of 9.16 t ha^{-1}.

Although the intra-year variability was similar for straw and grain yields for each cultivar, inter-year variability in straw yields was greater than that for grain yields. When the CVs of the grain yields and straw yields across the three years are calculated, straw yields show greater variability. The greater CV value for straw is a result of the higher straw yields in 2012. Xi19 showed greater variability in grain yields than Grafton and Cordiale. Xi19 was removed from the HGCA 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, HGCA). 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.

Larsen et al.'s (2012b) results indicate greater variability in straw yields than grain yields. Other researchers have also found wheat straw yields show great variability, more so than grain yields (pers. comm. Ethel White, AFBINI).

Stem and straw yield

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 straw density varied between treatments. The cultivars differed greatly in height but were not significantly different in terms of straw yield when considering total stem. This was also seen with chlormequat application lowering height but not significantly lowering stem mass. However, results from 2011 do not support this and to really understand the relationship, the plant number and tiller number are required.

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 (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.

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 (data from Roy, 2014) the only difference was for Maris Widgeon, which is an older non-semi-dwarf cultivar. Larsen et al. (2012b) 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 take the form of only two straw yield categories, high and low.

PGRs

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.

Nitrogen

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. However, 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.

2.6.2 Lodging assessments

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 HGCA’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).

In Baker et al. (1998), ear area is a determinant of the wind-induced force acting on the stem. An increase in ear area increases the force acting on the stem. As well as having the greatest HCG, Xi19 also had a much larger ear area than the other cultivars, which is likely to have further decreased the SFWS and RFWS relative to the other cultivars.

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.

2.6.3 Digestibility assessments

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.

The leaf-to-stem ratio might have had an influence on digestibility but as the ratio was not measured for the samples that were processed it is not possible to determine. However, the leaf-to-stem ratio could not explain all the differences in digestibility between Grafton and Cordiale as both leaf and stem components of Grafton had higher digestibility than Cordiale.

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).

The lower stem is the most likely location of stem failure (Berry et al., 2004), but this tends to be left on the field after harvest so any comparison of lodging susceptibility and digestibility needs to consider this. Therefore, the relationship between lower stem digestibility and upper stem digestibility needs to be addressed because the lower stem is the part of the stem that must resist lodging. It may be that the lower stem strength is correlated with upper stem strength but this needs to be determined.

2.6.4 Dual-purpose cultivars

From the data collected in the field experiments no cultivars were outstanding candidates for dual-purpose use. 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.

However, the differences in these characteristics were very minor and with only three seasons' of data from a single location, it is not possible to draw firm conclusions about these cultivars. For example, in the current experiment grain yield was lowest for Xi19, which does not reflect the average yields in the HGCA RLs where Xi19 was the highest yielding of the three cultivars.

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 (see **Chapter 6**) 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.

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 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 HGCA 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.

Further work is required to consider the impacts of N and PGRs on the yield components. One thing that must be considered is that the blocking design (split-split plot design) gave very low residual degrees of freedom for the PGR and N treatments making it difficult to gain significance. Using a field experiment design that maximises the residual degrees of freedom might facilitate identifying differences between treatments; however, this will require careful planning as PGR spray drift or N leaching between plots could prevent differences being found.

When selecting cultivars for use as DPCs, an economic analysis might provide better data on the most useful. The following chapter includes an economic analysis of the cultivars based on the average data from the three years of field experiments (**Tables 2.15a-c**). It must be noted that for some of these traits, the cultivars did not significantly differ.

Table 2.15a: Average values of the DPC traits for Cordiale.

Trait	PGR	Unit	2010	2011	2012
Grain (quadrat)	With PGR	t ha^{-1}	-	8.46	8.42
	Without PGR	t ha^{-1}	10.61	9.11	7.88
Total straw	With PGR	t ha^{-1}	-	4.18	7.90
	Without PGR	t ha^{-1}	5.08	4.76	7.64
Digestibility	With PGR	g g^{-1} biomass	-	0.40	0.14
	Without PGR	g g^{-1} biomass	0.34	0.39	0.14
Lodging	With PGR	m s^{-1}	-	10.39	12.27
	Without PGR	m s^{-1}	19.71	10.08	10.49

Table 2.15b: Average values of the DPC traits for Grafton.

Trait	PGR	Unit	2010	2011	2012
Grain (quadrat)	With PGR	t ha^{-1}	-	9.26	8.31
	Without PGR	t ha^{-1}	7.88	9.32	7.88
Total straw	With PGR	t ha^{-1}	-	4.39	7.71
	Without PGR	t ha^{-1}	3.89	5.00	7.86
Digestibility	With PGR	g g^{-1} biomass	-	-	0.16
	Without PGR	g g^{-1} biomass	-	-	0.15
Lodging	With PGR	m s^{-1}	-	13.50	11.90
	Without PGR	m s^{-1}	21.02	12.64	10.55

Table 2.15c: Average values of the DPC traits for Xi19.

Trait	PGR	Unit	2010	2011	2012
Grain (quadrat)	With PGR	t ha^{-1}	-	8.14	6.94
	Without PGR	t ha^{-1}	9.87	9.99	6.58
Total straw	With PGR	t ha^{-1}	-	4.82	7.52
	Without PGR	t ha^{-1}	5.35	5.60	7.97
Digestibility	With PGR	g g^{-1} biomass	-	-	0.15
	Without PGR	g g^{-1} biomass	-	-	0.14
Lodging	With PGR	m s^{-1}	-	11.75	9.62
	Without PGR	m s^{-1}	19.72	9.08	8.91

2.7 Conclusions

The main findings of this chapter are:

- Xi19 had significantly lower grain yield than the other cultivars.
- Total straw yield did not vary between the cultivars assessed but when simulating combine header height Xi19 produced significantly more straw than the other cultivars.
- Total straw yield was higher in the 2011-2012 field experiment than in the previous field experiments, probably a result of much greater water availability during the spring in 2012.
- Chlormequat application lowered plant height but a difference in stem yield was only found when the lower 15 cm of stem was excluded from the comparison. This appears to be because chlormequat application increased the weight of the lower stem.

- N application rate did not significantly influence straw or grain yields, and only had a limited influence on other characteristics. However, weather conditions may have meant that all plots had equal access to N.
- There were differences in digestibility between two of the cultivars and plant fractions differed with leaf blades being more digestible than peduncle which, in turn, was more digestible than the remainder of the stem. Higher digestibility rates were found with chlormequat application.
- Lodging differed between cultivars, with lodging susceptibility increasing with increasing height. Chlormequat application lowered lodging susceptibility.
- None of the cultivars assessed were outstanding candidates for use as DPCs though Grafton arguably represents a candidate cultivar for farmers growing feed wheat. A greater range of cultivars need to be assessed in the future.

Chapter 3: Value of dual-purpose cultivars

3.1 Introduction

In this chapter the potential value of dual-purpose cultivars (DPCs) to farmers is considered. Models are used to determine gross margins (GMs), which are standard values used in farmer enterprise decisions, for current cultivars using data from **Chapter 2**, as well as for hypothetical cultivars. The GMs indicate the potential value of these current cultivars as DPCs, as well as indicate the merit of developing new cultivars specifically for use as DPCs.

3.2 Literature review

Gross margins, the value of the output less the variable costs, provide an aid to farmers when making decisions about which crops to grow (Nix, 2013). They do not include fixed costs, which are costs that arise regardless of the enterprise choices (e.g. rent, labour, machinery). GMs do not give a complete view of the finances and should not be used as a proxy for profit, but they do provide a strong means of determining the value of a farming enterprise. Farmers consider GMs when making decisions about which cultivars to grow (see **Chapter 6**), so the uptake of DPCs will depend on them having a competitive GM. The Agricultural Budgeting and Costing Book (ABC; Agro Business Consultants Ltd.), the John Nix Farm Management Pocketbook (Nix, Agro Business Consultants Ltd.) and the farm business survey website (http://www.farmbusinesssurvey.co.uk) are guides available to farmers for making decisions about farm enterprises.

This literature review considers the current value of wheat grain, followed by a more in depth examination of the current price of straw and the aspects that determine its value to farmers.

3.2.1 Cultivar selection

Chapter 2 considered the variability in current cultivars for use as DPCs. It may be possible that one of these cultivars, or a different existing cultivar, could perform a role as a DPC. However, there were no standout candidates for use as DPCs, which suggests that to achieve the optimum benefits will require a breeding programme.

Whether a breeding programme is feasible depends on a number of factors. Cultivar breeding programmes are expensive and time-consuming so it is important to know if there will be a market for the cultivars. Research has highlighted the difficulty of breeding new cultivars, in particular meeting both farmer and end-user preferences (Dahl et al., 2004); so the DPC must be desirable both to the farmers and the biofuel processors. Breeders face uncertainty about premiums for quality traits, making it difficult to predict the importance of traits to users. Digestibility of straw would only become a target breeding trait if processors will pay a premium for high digestibility.

It is important to consider spatial aspects when developing new cultivars (Dahl et al., 2004). The potential size of a market for straw for biofuel production is unknown but the smaller it is the less the demand for the development of a DPC. There is also the issue of breeding for a particular niche, as the time-lag between starting and finishing a breeding programme might mean that the desired characteristic is no longer of interest to farmers by the time the cultivar reaches market.

Cultivar choice decisions depend on a number of factors. Kansas farmers choose cultivars based on production characteristics, such as relative yields and yield stability (Barkley & Porter, 1996). End-use quality characteristics were also important, but often farmers would choose higher yields over better end-use quality. However, selection criteria vary between regions, with differences in the importance placed on agronomic factors, such as yield, and end-use qualities varying with markets, information and availability of cultivars (Dahl et al., 1999). In Denmark, farmers most frequently based cultivar decisions on yields (Detlefsen & Jensen, 2004).

The value of straw will determine whether selecting cultivars as DPCs is economically viable. Annicchiarico et al. (2005) examined the value of Algerian durum wheat cultivars based on straw and grain yield and found that older cultivars had less grain than newer cultivars but remained competitive due to higher straw yields. However, grain yields are lower in this region compared to the UK whilst demand for straw is greater meaning the value of straw relative to grain is much higher.

There are indices available for a large number of cultivar traits (e.g. disease scores, lodging resistance, grain quality traits; see HGCA RLs); as there are various trade-offs between these traits it makes it difficult to identify the most appropriate cultivar to grow. Tools have been developed for facilitating these cultivar selection decisions by assessing cultivar value based on their traits. Nelson and Meikle (2001) developed the NIAB Gross Margin Model for assessing cultivar value with the option of choosing disease burden and prices and Detlefsen & Jensen (2004) developed a model for Danish wheat cultivars based on multiple characteristics.

Sylvester-Bradley et al. (2007) identified the best cultivars for producing FGBs based on potential bioethanol yields. They suggest that in the future processors might offer premiums for the cultivars best suited to biofuel production; however, there is no guarantee that a premium will ever be offered. This leaves crop breeders with uncertainty about the value of cultivars that have been bred to have higher biofuel yields.

3.2.2 Grain value

3.2.2.1 Grain price

As wheat grain is a global commodity, prices are influenced by supply and demand aspects operating on a global scale. In the UK, grain prices have varied drastically over the past ten years (**Fig. 3.1**); between 2000 and 2007 the average feed wheat price was £71.49 t^{-1} with the highest price £109.30 t^{-1}. During 2007 prices increased £91.30 t^{-1} at the start of the year to £168.30 t^{-1} in September and price volatility increased matched by similar volatility globally, an event termed *the world food price crisis*. There are a number of competing theories for this volatility in price (McCalla, 2009); the main reason appears to be fluctuation in supply and demand with confounding influences from factors such as speculative trading. There was also an increase in demand, for example from their use as biofuel feedstock, at the same time as a reduction in supply due to events such as natural disasters.

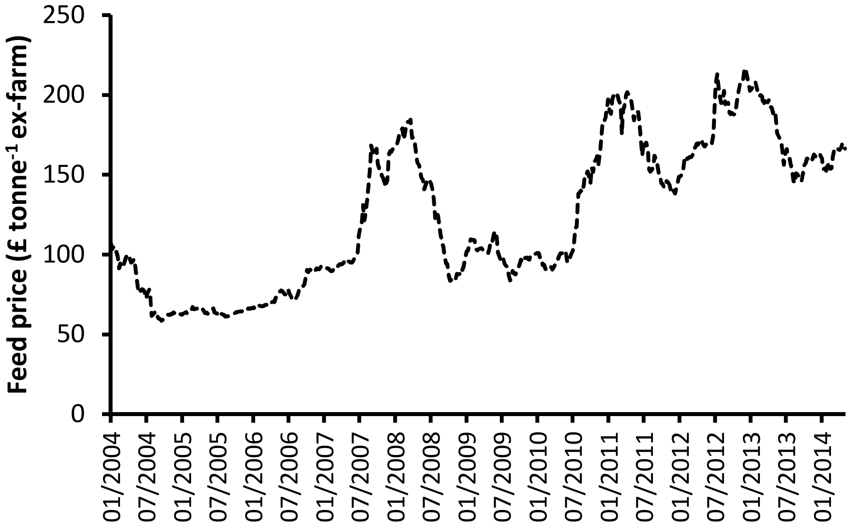


Figure 3.1 Ex-farm feed wheat grain prices in the UK, January 2004 to April 2014. Data from HGCA (2014).

Although prices returned to close to pre-crisis levels in 2009, another price spike occurred in 2011 and grain prices have remained relatively high ever since suggesting a permanent structural break in prices. It is unclear how prices will change in the future with high uncertainty about supply and demand. A number of predictions have been made about future grain prices but there appears to be no consensus.

3.2.2.2 Grain premium

Grain price varies with markets but premiums can be paid for grain that meets minimum values for criteria such as protein content, Hagberg falling number (HFN, a measure of activity of the enzyme alpha-amylase) and bulk density (Hollins et al., 2006). Discounts are applied depending on the moisture content and the presence of contaminants (e.g. foreign material, mycotoxins; Barkley & Porter, 1996). The prices paid and the minimum levels for these criteria will depend on the market the grain is sold in.

Wheat grain is highly variable in its characteristics and this variation is important when choosing grain that is optimal for a particular end-use. Grain is broadly classified into three categories: bread-making quality wheat; biscuit and cake making quality; and animal feed quality. These qualities are in part fixed in cultivars (e.g. see Nabim groupings for wheat cultivars) but also dependent on management practices, with bread-making quality grain requiring larger applications of N fertiliser to achieve specification (Nix, 2013). Cultivars for bread-making quality tend to be lower-yielding than those for feed so farmers expect to be paid more for grain of this quality. The bread-milling premium is also highly variable (**Fig. 3.2**), with the three biggest drivers being the level of HFN (i.e. the supply of bread-milling quality grain), the demand for feed grain, and the overall supply of grain (Hollins et al., 2006).

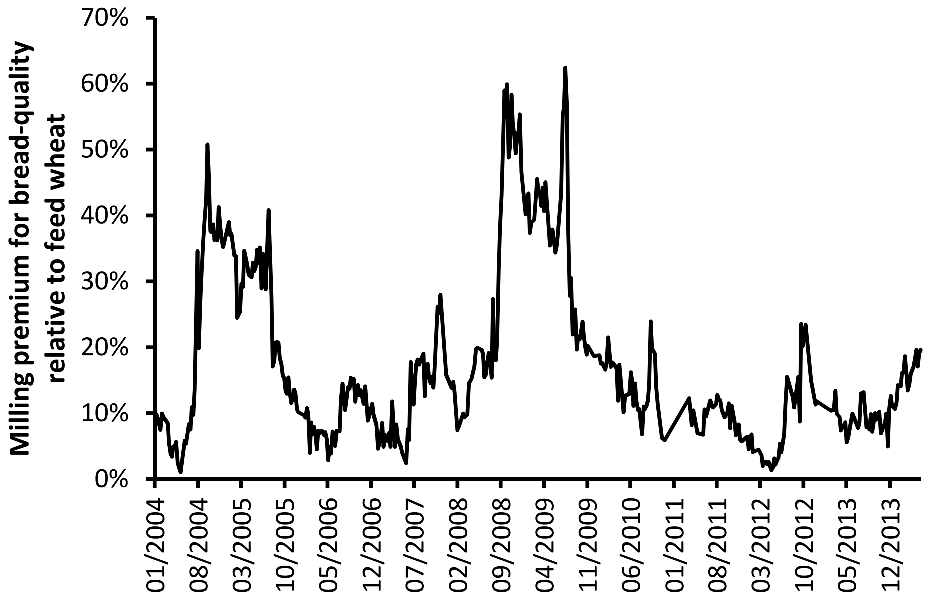


Figure 3.2 Percentage increase in price of bread milling wheat relative to feed wheat. Based on weekly bread milling and feed wheat prices from the HGCA (2014).

3.2.3 Straw value

Straw is a by-product of the production of grain. 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. 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). These aspects are considered in more detail below.

3.2.3.1 Current price

Average straw prices have increased over the past ten years (**Fig. 3.3**). The highest prices were found in summer 2012, which was a very wet harvest, suggesting a lack of supply due to difficulties baling. There appears to be both within year and yearly variation with the highest prices occurring in the summer before grain harvesting has occurred.

Unlike grain prices, which tend to be the same throughout the country, straw prices vary greatly throughout the country. This is because they are highly dependent on local markets, with the highest prices in mixed farming and livestock parts of the country and lower prices in the predominately cereal-producing areas (ABC, 2013). Straw transportation costs are high (see **Chapter 4**) and this tends to limit the selling of straw beyond local markets.

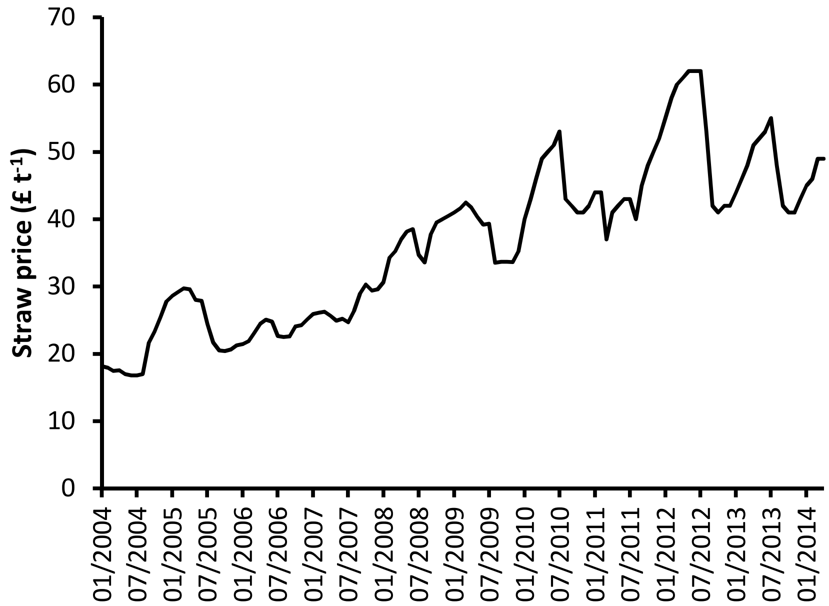


Figure 3.3 Average prices for big square baled wheat straw in England and Wales from January 2004 to April 2014, price per tonne ex-farm. Data from Defra (2014).

Modelling a future straw SGB scenario in the UK requires information about straw prices but using average straw prices could provide inaccurate results. As an example, Wang et al. (2013) used a price of £52 t^{-1} for LCA allocation (see **Chapter 5**) and the same authors used a price of £38 t^{-1} for modelling the biofuel production costs (Littlewood et al., 2012). Both prices were calculated from average straw prices but different timespans were used giving very different prices. It is possible that a structural break in the price has occurred in the past five years, meaning that taking an average price including prices from before that point could underestimate prices. With variation in prices throughout the year, the average price must be for a whole year to not be skewed by that variation.

It is likely that the price paid for straw for biofuel production will differ from the England and Wales average. In the UK there is a market for straw as a feedstock for the production of electricity. The majority of straw-for-energy contracts are for 8-12 years, and feature an index-linked price that is typically upwards of £40 t^{-1} (Spackman, 2012). However, experience in Denmark shows that signing long-term, indexed-linked contracts can be expensive for power plants, and most straw is now traded on the free market via competitive bidding (Skøtt, 2011).

3.2.3.2 Replacement nutrients

Fertilisers are required to replace the nutrients removed in straw. However, the amounts of nutrients removed in straw can vary greatly (e.g. El-Nashaar et al., 2010), which means that fertiliser recommendations also vary greatly. **Table 3.1** provides fertiliser replacement rates from multiple sources. These values represent different regions though it is unclear whether the differences between regions represent actual differences or uncertainty in straw nutrient content. Even in the values for the UK there is considerable variation (compare Abel, 2009, and Punter et al., 2004). The difference could result from different methods for assessing nutrient content and some of the figures could be based on small samples. For example, HGCA (2009) provide the caveat that the value for MgO is based on only a few samples. It is unclear why Punter et al. (2004) and OMAFRA (1999, as cited by Levelton Engineering Ltd., 2000) have such high values. Punter et al. (2004) gave the amounts per hectare without giving a straw yield making the amount unclear (the values in the

Table are assuming a 5 tonne yield), but it might be that these values are for total non-grain biomass and not baled straw.

Potassium (potash or K_2O) has the largest fertiliser requirement but it also shows considerably variability due to it being easily leached from straw by rain (RB209, 2010). Smaller amounts of phosphate (P_2O_5) are required but it is not leached from straw so these values are more consistent. RB209 (2010) provides P and K fertiliser requirements for UK straw production. However, it has been suggested that these values have been overestimated; Abel (2009) refers to data from Ely straw-fired power station where eastern England-sourced straw averaged lower nutrient values that those in RB209.

Table 3.1: The amount of fertiliser required to replace nutrients removed in straw (per 1 tonne fresh material) from multiple literature sources.

Source	Region	K_2O (kg)	P_2O_5 (kg)	N (kg)	SO_3 (kg)	MgO (kg)
ABC (2013)	UK	10.0	-	-	-	-
RB209 (2010)	UK	9.5	1.2	-	-	-
Abel (2009)	UK	5.8	0.5	-	-	-
OMAFRA (1999)[1]	E. Canada	38.2	7.6	18.3	-	-
Alberta Agriculture (1999)[1]	W. Canada	18.1	4.2	6.0	-	-
Punter et al. (2004)[2]	UK	28.4	5.5	13.6	-	-
Wortmann et al. (2008)	USA	7.5	1.5	5.5	2.5	-
MAFRD (2014)	C. Canada	14.0	2.1	6.3	7.0	-
IPNI (2008)	USA	12.0	1.7	7.0	1.5	0.7
HGCA (2009)	UK	9.5	1.2	-	-	1.3

[1]as cited by Levelton Engineering Ltd., 2000; [2]Values were given per hectare so these values are assuming a 5 t ha^{-1} straw yield.

Crop residue removal reduces soil N content (Thomsen et al., 2003); however, RB209 (2010) does not recommend extra N to replace that removed in residue, possibly because the majority of N in residues left in the field does not become available until later seasons and it actually immobilises other N until after the following season (Powlson et al., 1985). However, over a longer time period, the N will be become available and, therefore, the N removed in the straw should be considered.

Some sources recommend additional sulphur (S) and magnesium (MgO). There are other micronutrients removed in straw. For example, ash samples from Ely straw-fired power station found 21 g Ca kg^{-1} straw (Newman, 2003). The RB209 (2010) recommends that these fertilisers should be added when there is a deficiency rather than yearly, which means that it is difficult to link the nutrients taken off the field in the straw with the amounts of fertiliser that need to be applied. There are significant amounts of sulphur in straw (Sager, 2012) but S is often not considered. This maybe because historically significant amounts of S are naturally deposited on the field reducing the need for additional fertilisers. However, S should be taken into account as this nutrient is becoming more important following restrictions on power stations which have led to less sulphur emissions and hence less sulphur deposition on fields (Kilburn, 2011). Not taking account of these nutrients might mean that the value of the nutrients removed in the straw is underestimated.

3.2.3.3 Fertiliser costs

In the UK, the price of fertiliser is driven by global markets (AIC, 2014). These prices have a cyclical pattern resulting from periods of over- and under-capacity, as a well as correlation with oil prices (Yara, 2012). Fertiliser prices were fairly consistent between 2000 and 2006, and then increased significantly during the financial crisis of 2007/2008 before eventually decreasing to the current values (**Fig. 3.4**). Prices are expected to decrease further as the market is undergoing a significant transformation, which is partly the result of changes in energy markets (Baffes & Cosic, 2014).

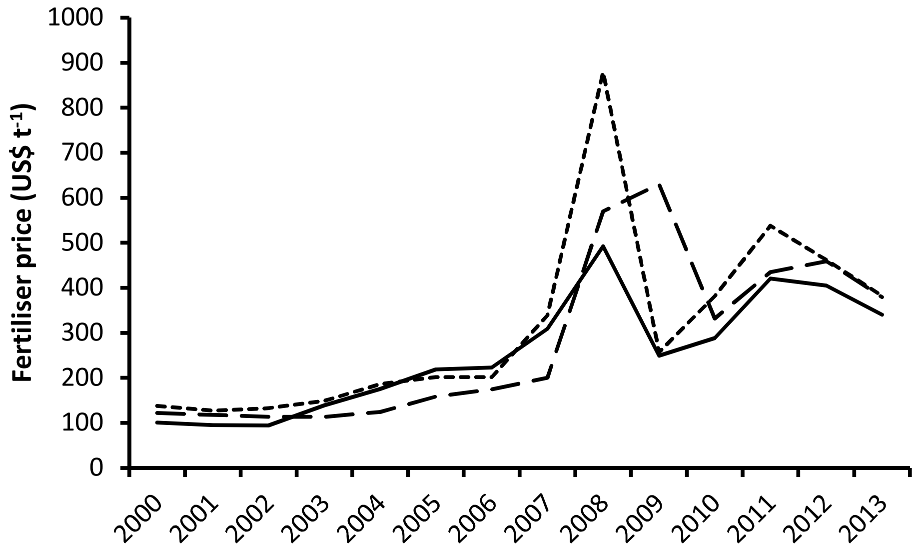


Figure 3.4: Global fertiliser prices for urea, triple superphosphate and potassium chloride between 2000 and 2013. Fertilisers: urea (solid line); triple superphosphate (small dashes); potassium chloride (large dashes). Data from World Bank Commodity Price Data (Anon, 2014)

3.2.3.4 Collection costs

Quantifying the costs for the collection of straw is difficult due to the variability in the operations that are used and the specific conditions of the site. For example, different balers can be used giving different sized bales and densities. It is likely that a biofuel refinery will use large rectangular bales (i.e. Hesston bales) as these are used by the current straw-fired power stations (Newman, 2003; Skøtt, 2011). Specific site-dependent conditions include weather conditions, which can slow baling and incurring costs through wasted time (Sokhansanj et al., 2006), and field size, which determines the amount of time taken for baling equipment to turn on the headlands (Nilsson, 1999).

Increasing straw yield will influence collection costs. Combine harvester speed and fuel use are dependent on the amount of material passing through them; increases in straw yield result in decreased speed and increased fuel use (Hill et al., 1987; Kehayov et al., 2004). For other machinery, it is unclear whether there is a direct relationship between straw yield and collection costs or if the efficiency is influenced by yield. The IBSAL model (Sokhansanj, et al., 2008b) modelled straw collection equipment as being optimised to a certain yield with productivity being lower at yields above and below that optimum. However, unpublished work by the company ANTARES found the fuel use and the time taken to harvest straw per hectare does not vary significantly with yield, suggesting that higher straw yields will have a greater efficiency and, therefore, reduced costs per bale (Clark, 2012).

Research has considered total straw collection for a biorefinery, attempting to produce an optimum collection system by considering aspects such as the optimum amount of equipment required. Studies have shown increasing straw yields can lower overall collection costs (Nilsson, 2000; Stephen et al., 2010). An optimised system requires a single organisation collecting the straw. It is unclear whether an optimised system would be used in the UK as straw is likely to collected and transported by multiple parties including by the farmers themselves and third-parties such as agents, as can be seen from Ely straw-fired power station (Newman et al., 2003).

The actual costs depend on whether the farmer has equipment and carries out the operation or uses contractors. As described above, Ely straw-fired power station uses a mix of straw baled by the farmers themselves and straw baled by contractors (Newman, 2003). Contractor prices are variable but it is possible they could provide lower costs by being able to maximise the use of equipment as well as invest in equipment. This offers the opportunity to reduce costs by better coordinating operations. However, a guaranteed market for straw might mean more farmers invest in baling equipment. The allocation of costs is also important in determining the costs of straw collection. For example, the IBSAL model allocated 10% of combine harvesting costs to the residue (Sokhansanj, et al., 2008b) whereas normally all combine harvester costs are allocated to the grain.

3.2.3.5 Storage

Biorefineries will need straw throughout the year but as straw harvest only occurs a few months of the year the majority of straw will need to be stored. The straw-burning bioenergy plant at Ely only has feedstock capacity for approximately four days and straw is collected from farms year-round with straw stacks left standing in the field for up to 12 months (Newman, 2003). During storage it is possible that losses of dry matter will occur with the extent of these losses dependent on the weather conditions, the technology used and the status of the plant material, the duration of storage (Hamelinck et al., 2005), bale type, whether the bales are protected (Coble & Egg, 1987) and the moisture status of the bales (Nilsson, 1999). As well as dry matter losses, the quality of the material can also deteriorate if moisture levels are too high (Nilsson, 1999). If incorrectly stacked, bales can be crushed and will not be able to be sold. There is also a risk of vandalism or arson. For example, a suspected case of arson led to a loss of £60,000 of straw for a farmer (Case, 2013).

Taking into account dry matter losses during storage, as well as during transport, is important because the emissions and costs related to upstream processes are being concentrated (Thornley, 2008). For example, if 5% of material degrades, that is 5% of nutrients and harvesting costs that are lost from the system.

3.2.3.6 Other costs

As discussed in **Chapter 2**, there are other considerations that are harder to value. Three of the biggest concerns for farmers about baling straw are timeliness issues, perceived benefits of straw incorporation to the soil and compaction from baling equipment (Glithero et al., 2013b; see **Chapter 6**). Timeliness issues can result in a delay in establishing the next crop, which could lead to reduced yields. Barken et al. (1987) found soil compaction from baling in wet conditions led to a 25% yield reduction in following crop. The incorporation of straw can influence soil water storage, improving drainage on heavier soils and aiding water retention of light soils (Henly, 2012). These effects are site-dependent but can have significant effects on farms.

Baling contractors have sought to reduce these impacts. New equipment has been developed that minimises compaction, and some contractors use controlled traffic using fixed tramlines (Anon, 2012a). Some contractors work 24 hours a day to reduce timeliness issues.

Chopping and incorporating straw incurs costs which are avoided when straw is baled. Chopping straw leads to higher fuel use (e.g. Glithero et al., 2012, assume combine harvester fuel use is 20% higher when chopping is included), and extra time taken. Abel (2009) mentions research conducted by the British Straw and Hay Merchant Association (BSHMA) that found a combine requires 70-100 hp of extra power for chopping straw, which adds up to 30%, or £18.75 hr^{-1} of additional fuel costs (approximately £7.35-8.15 based on a combine rate of 2.30-2.55 ha hr^{-1}). This also results in a reduction in output by up to 25%, or

10 ha day^{-1}. There is also the additional cost of new blades at around £1000 yr^{-1}. However, it is unclear where this data is from and what conditions they were calculated for; the higher costs might be a result of experiments on high straw yields and/or tough straw. The additional costs of chopping suggested by this source are also higher than those given in the National Association of Agricultural Contractors (NAAC, 2012).

Other avoided costs are hard to quantify and are, therefore, excluded from straw value estimates. The same BSHMA study mentioned above also claims that ploughing straw back into the soil can incur extra costs for establishing the following crop (an extra £30 ha^{-1}, Abel, 2009). However, incorporating straw into some soils makes the soils more workable, and, therefore, saves money for preparing land. With the removal of straw there can be a reduced slug, weed and disease risk, hence reducing expenditure on pesticides such as molluscicides (Profi, 2009).

3.2.3.7 Straw value estimates

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).

Aden et al. (2002) calculated the cost of collection and delivery of corn stover to a biorefinery. The baling accounted for nearly half the costs (**Fig. 3.5**). Nearly a fifth of the value was for a farmer premium, which was expected to cover a profit for the farmer but also as a way to cover the costs that are much harder to quantify such as soil impacts.

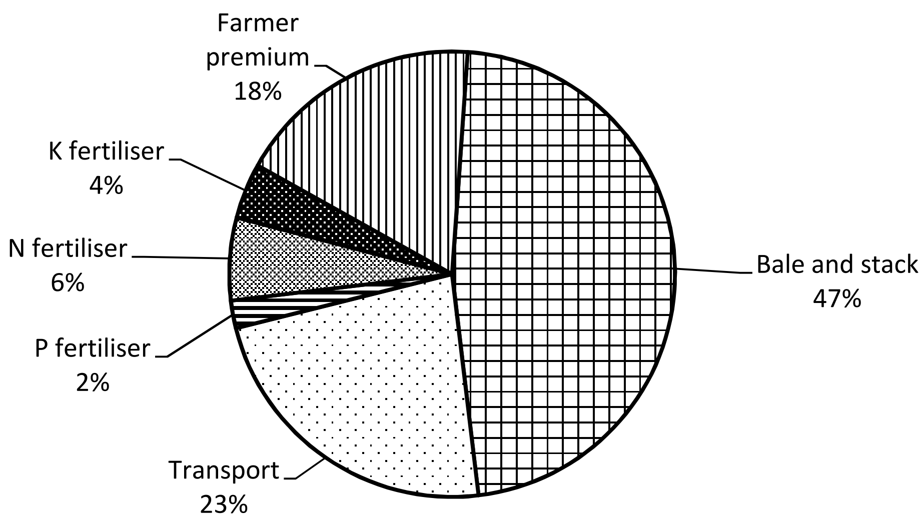


Figure 3.5 Breakdown of the costs of corn stover, taken from Aden et al. (2002)

The UK crop residue supply chain has not been assessed to the same extent as that in the US. 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 would benefit farmers. To make estimates easier, these estimates assume that the processor purchases the straw at the farm gate so the farmer does not include haulage costs, but it also assumes that farmers do not own baling equipment and, therefore, have to contract out the work.

ADAS (2008) estimated that a price of £31.84 oven dry tonne^{-1} (odt^{-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.

3.2.3.8 Straw for biofuel

A biofuel refinery could provide a substantial new market for straw but it is unlikely that straw suppliers will be paid more than the current contracts for straw for energy (upwards of £40 t^{-1}, Spackman, 2012. Biorefineries are likely to be constructed where there is currently only a limited market for straw, meaning that there should not be competition for this resource and, therefore, will not increase the price. To demonstrate this, Eco2 UK failed to gain planning permission for a straw-burning facility because of concerns that there was insufficient straw available to not have an influence on other straw-users (Tasker, 2013).

Another aspect limiting the price that will be paid to farmers is due to the costs of producing SGBs. Hamelinck & Faaij (2006), in modelling biofuel production, found that feedstock costs account for 45 to 58% of total production costs for SGBs, depending on conversion efficiency and applied technology whilst Carriquiry et al. (2011), reviewing SGB production estimates, found that feedstock procurement accounted for 32 to 52% of total production costs. As they contribute such a large component of price, the SGB costs are highly sensitive to feedstock price. For that reason it is likely that biofuel processors will seek to pay the lowest possible price for straw.

3.3 Aims

- Determine the minimum selling price for straw.
- Determine the gross margins for straw for different straw prices.
- Determine the value of real and hypothetical cultivars based on their characteristics.

3.4 Methodology

3.4.1 Introduction to the models

Two models for calculating GMs were produced. Model 1 uses average values to calculate the breakeven straw price and average GM that could be expected for supplying straw from a number of hypothetical cultivars with differing straw yields and digestibility. 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. 3.1, 3.2**).

$$GM_s = \left(SY \times \left(S_p + P_d\right)\right) - VC \qquad \textbf{Eq. 3.1}$$

$$VC = \left(SY \times (F \times FP)\right) + CC \qquad \textbf{Eq. 3.2}$$

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}).

Model 2 uses Monte Carlo simulation to account for variability in these values so as to give a GM output distribution. The model is firstly run to calculate a straw breakeven price distribution. It is then used to calculate the potential value of the cultivars assessed in **Chapter 2** as DPCs.

Both models are constructed using Excel, with Model 2 using the Microsoft Excel add-in, Risk Solver Platform (RSP), version 9.5 (Frontline Solvers, Inc., NV, USA), which allows the construction of Monte Carlo simulation models (Frontline Systems, 2011).

3.4.1.1 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 will be used in this chapter, as well as in the logistics analysis (**Chapter**

4) and LCA (**Chapter 5**), to assess the impact of potential ranges in yields and digestibilities.

Nine hypothetical cultivars are assessed. For these cultivars, the grain yield and quality is assumed to be equal. The straw yields used are 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, 2012a) and the upper value represents a cultivar managed for higher straw yield. A value of 16% MC is used based on the average value at Ely (Newman, 2003) and it is assumed that the MC is 16% at the farm gate and the biorefinery gate.

Three straw digestibility levels are modelled (represented as D1, D2 and D3). As discussed in **Chapter 2**, 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., 2012b). 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 are 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 is taken as 335 L odt^{-1} straw (based on Borrion et al., 2012). The intermediate value (D2) is 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 are: 2.54 kg L^{-1} (D1), 2.48 kg L^{-1} (D2), and 2.42 kg L^{-1} (D3).

3.4.1.2 Field experiment cultivars

For model 2, the mean for key traits found in the experimental work described in the previous chapter are used. The data for grain and straw yields and lodging failure wind speed are used. This will be conducted for the results for plots without chlormequat treatment as less data is available for chlormequat-treated plots.

Digestibility measurements were only collected for one cultivar (Cordiale) for all three years and the values from the final field experiment were much higher than the previous two years. It is also unclear how the results collected would correspond to actual ethanol yields at the industrial scale. Because of this the cultivars are not assigned digestibility levels. Instead, the digestibility premiums will be added to the cultivars to see its relative influence on cultivar value and to see if it alters cultivar value rankings.

As the cultivars differed in their uses, grain premium prices are awarded to those of milling quality. There are two levels: biscuit and cake milling quality and bread making quality, with a higher premium for bread making quality grain.

3.4.1.3 General model assumptions

The model assumes:

- Grain and straw prices are fixed; that is, they do not vary with market supply and demand, hence this analysis represents a situation where overall average market prices are held constant.
- It is assumed that farmers would only grow these DCPs when they intend to harvest the straw. On average farmers grow more than two cultivars at a time (see **Chapter 6**). Therefore, when farmers grow these cultivars, the prices (e.g. chopping, ground preparation) are not increased for the crops where the straw is not being harvested. For example, when a farmer plans to chop the straw, the farmer grows a cultivar with low straw yields so as to avoid the additional fuel use and time of chopping a greater straw amount.
- Farmers do not own baling equipment and instead use contractors.
- Baling is not disrupted by inclement weather so there are no additional costs from delays in straw harvesting.

3.4.1.4 Gross margins and variable costs

The model calculates gross margins for the cultivars from the value of the outputs and the 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 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 will provide a comparison of the price differences between the cultivars.

3.4.1.5 Variability and uncertainty

The Monte Carlo simulations in model 2 account for variability in the input parameters. The Monte Carlo simulation will be run 1,000 times to generate value distributions. As with Gibbons et al. (2006), where information on the shape of the parameter distributions is not available, a triangular distribution was used. This distribution specifies a minimum and maximum value, and a most likely value is specified which forms the apex of the triangular distribution. This distribution preserves any asymmetry in the values as the apex can be closer to the minimum or maximum. The variability in grain and straw yields is modelled in model 2, as well as the likelihood of lodging events occurring.

3.4.2 Model 1

3.4.2.1 Grain value

The GM for the grain is calculated as the yield multiplied by the price, less the variable costs. For model it is assumed the crop is a first wheat after a non-cereal break crop, which is the most common combinable cropping situation in the UK (ABC, 2013) and it is a feed wheat. Gross margins are taken from grain prices and average variable costs in Nix (2013), equalling £779 ha^{-1}, (grain value £155 t^{-1} and VCs of £461 ha^{-1}) and the ABC (2013), which gives £743 ha^{-1} (grain value £150 t^{-1} and VCs of £457 ha^{-1}) based on a straw yield of 8 t ha^{-1}. The average £761 ha^{-1} is used in the analysis (which, when assuming an 8 t ha^{-1} grain yield, gives a GM of £95.13 t^{-1}).

For model 2 there are milling cultivar and feed cultivars. The variable costs for milling wheats are higher than those for feed wheats because a greater amount of N is required. For the variable costs the values in Nix (2013; £514 ha^{-1}) and ABC (2013; £507 ha^{-1}) are used to give an average of £510.5 ha^{-1}.

The milling premium prices for use in model 2 are taken from Nix (2013) and ABC (2013). Nix (2013) gives average premium prices as £35 t^{-1} for bread quality and £12 t^{-1} biscuit. In their calculations for average milling premium they assume a 25% failure rate in achieving the premium. ABC (2013) gives a lower value for bread-quality grain (£20 t^{-1}) but the same value for biscuit-quality (£12 t^{-1}). In this analysis an average value of £27.5 t^{-1} is used for bread-quality and £12 t^{-1} is used for biscuit-quality. The failure to gain specification is taken as a lodging event occurring (see below).

3.4.2.2 Straw prices

It is unclear how much would be offered for straw of biofuel production. The model will look at multiple values of straw to assess the relationship between grain and straw yield. GMs will be 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.

3.4.2.3 Straw digestibility premium

The model will consider 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.

3.4.2.4 Fertiliser requirements

The various values for replacement nutrients were given in **Table 3.1**. As it is unclear how applicable the values from other regions are to the UK, the values most appropriate to the UK are used (**Table 3.2**). No UK values for S are available so this is given as an average of the three sources. The value for N fertiliser is quite variable. The two largest values are discarded and an average of the four values is taken. No sources gave figures for Ca so this is excluded from the model.

Table 3.2: Fertiliser requirements per tonne straw (fresh weight)

Nutrient	Mean (kg)	Source
K_2O	9.5	RB209
P_2O_5	1.2	RB209
N	6.2	Alberta Agriculture, Wortmann et al., IPNI, MAFRD
MgO	1.3	HGCA
SO_3	3.7	Wortmann et al., IPNI, MAFRD

3.4.2.5 Fertiliser prices

Fertiliser prices have been highly variable in the past and, although they are expected to decrease in price, predicting fertiliser prices is difficult. Nix (2013) and ABC (2013) provide estimates of fertiliser prices for the 2014 growing season and these values are used in the model. Both sources provide values for N, P_2O_5 and K_2O and the means of the highest and lowest values in these sources are used as the spot prices in the model (**Table 3.3**). Nix (2013) has the following prices: N = £797 t^{-1}; P_2O_5 = £707 t^{-1}; K_2O = £542 t^{-1}, whilst the ABC (2013) gives these prices: N = £768-858 t^{-1}; P_2O_5 = £609-717 t^{-1}; K_2O = £475-533 t^{-1}.

Neither Nix (2013) nor the ABC (2013) provides individual values for S and MgO, and the costs must be estimated from the cost of blends. Magnesium sulphate (26% MgO and 53% SO_3) costs £270-300 t^{-1} (ABC, 2013). This is equal to £1,038-1,154 t^{-1} MgO and £509-566 t^{-1} SO_3. Sulphur is in nitrogen sulphate (30% SO_3) for £267 t^{-1} and sulphate of ammonia (60% SO_3) for £270 t^{-1} (Nix, 2013) or £235-260 (ABC, 2013). This is equal to £890 t^{-1} and £450 t^{-1}

(£391-£433). It appears that N is the more expensive component so the price for S is based on the price on sulphate of ammonia.

Table 3.3: Average fertiliser prices delivered

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

3.4.2.6 Contractor prices

Contractor fees were mainly based on average values from the National Association of Agricultural Contractors (NAAC, 2012). Baling was £6.55 for a 1.2 x 1.3 x 2.5 m Hesston bale (NAAC, 2012). The weight of the bale is assumed to be 517 kg based on Newman (2003).

Loading and unloading of bales is taken as £0.58 bale^{-1} based on the cost for stacking (£35 hr^{-1} for a forklift/telehandler + man; NAAC, 2012) and assuming 1 minute bale^{-1} (based on Rogers & Brammer, 2009).

Transport of bales is taken as £1.46 bale^{-1} assuming 1 km transport distance (2 km there and back), with the trailer carrying 18 bales and a speed of 24 kmph (based on Nemecek & Kägi, 2007). The time taken to deliver (5 minutes) plus time waiting (18 minutes at each end) gives a total of 41 minutes and 2.28

minutes bale^{-1}. At £38.50 hr^{-1} for a tractor, trailer and man (NAAC, 2012), this gives a price of £1.46 bale^{-1}.

Taken together, this gives a total contracted price per bale of £9.17 (£17.74 t^{-1}), which is higher than the £10 bale^{-1} contractor price assumed by Banham (2011) but similar to the £15 bale^{-1} used by ADAS (2008).

3.4.2.7 Chopper credit

When the straw is baled the straw does not need to be chopped. The credit from not using the chopper on the combine is allocated to the straw; as this is given as a per hectare value, this credit must be divided by the straw yield on that hectare. The NAAC (2012) give average contractor prices for combining of £85.22 ha^{-1} with an extra £6.79 ha^{-1} for using the chopper, whilst the ABC (2013) suggests an extra 5% in costs for chopping straw with a price of £75-95 ha^{-1} (an average of £4.25 ha^{-1}). The average of these values, £5.52 ha^{-1}, is used in the model.

3.4.3 Model 2

3.4.3.1 Cultivar traits

As values were collected over a three year period, the model will randomly select a year, with equal probability of selecting each. The mean values from that year for grain and straw yields (at 16% MC) and failure wind speeds will be used in the calculations (**Table 3.7**). Baled straw yields are calculated as 60% of total straw yields assuming that 50% of total non-grain biomass is harvested (Sylvester-Bradley et al., 2008), and chaff contributes 20% of non-grain biomass (based on calculations from the field experiments).

3.4.3.2 Fertiliser requirements

In the Monte Carlo model, to account for the variability in the values for replacement nutrients, triangular distributions will be used based on the minimum, maximum values and the apex of the triangle will be centred on the mean of the values (**Table 3.4**). The values in the table are mean values in their own right so basing the minimum and maximum values for the distribution means that the full range is not captured. However, without further information it is not possible to provide a more accurate distribution.

P_2O_5 and K_2O distributions are based on the minimum and maximum values in the literature for UK values, excluding Punter et al. (2004), with the apex of the distribution centred on the average of these values. N is based on the sources used in model 1. MgO and S distributions are based on the available values for these.

Although the nutrients removed in the grain will depend on the yield, for the current model it is assumed that the flat rate of fertiliser is used regardless of the grain yield. However, milling and feed wheats have different requirements for N fertiliser and this will be reflected in the variable costs for the different cultivars.

Table 3.4: Maximum, minimum and most likely values for the fertiliser requirements used in the model (per 1 tonne wet material). The three parameters represent a triangular distribution.

Fertiliser	Min. (kg)	Max. (kg)	Apex (kg)
K_2O	5.8	10	8.4
P_2O_5	0.5	1.2	0.85
N	5.5	7	6.2
MgO	0.7	1.3	1
SO_3	1.5	7	3.7

3.4.3.3 Fertiliser prices

For the Monte Carlo simulations, it is assumed that Nix (2013) and ABC (2013) cover the range with the mean value being the middle of the minimum and maximum values (**Table 3.5**).

Table 3.5: Values for the triangular distributions for use in the Monte Carlo simulations for the price of fertiliser

Fertiliser	Min. (£ t^{-1})	Max. (£ t^{-1})	Apex (£ t^{-1})
K_2O	475	542	508.5
P_2O_5	609	717	663
N	768	858	813
MgO	1038	1154	1096
SO_3	391	450	420.5

3.4.3.4 Contractor prices

These values were used in making the distributions for the Monte Carlo analysis. A short online-survey was produced and distributed to members of the NAAC to look at variability in these prices. The lowest and highest values were taken with the average value from NAAC used as the most likely value in a triangular distribution (**Table 3.6**).

Table 3.6: Contractor prices for baling straw and moving straw bales to an on-farm storage point for the Monte Carlo simulation.

Operation	Minimum (£ bale^{-1})	Maximum (£ bale^{-1})	Most likely (£ bale^{-1})
Baling	5.75	7.25	6.55
Loading	0.52	0.63	0.58
Transport	1.25	4.00	1.46
Unloading	0.52	0.63	0.58

3.4.3.5 Chopper credit

The chopper credit is calculated using a triangular distribution with a minimum of £4.25 ha^{-1} (based on ABC, 2013) and a maximum of £6.79 ha^{-1}, (based on NAAC, 2012) with the mean as the most likely value.

3.4.3.6 Lodging

SFWS was used to calculate the lodging risk. It was compared to a Gumbel wind distribution (showing the likelihood of the wind reaching a certain speed per year; **Fig. 3.6**; from Berry et al., 2003c) and from this a probability of a lodging event occurring was taken as the probability of the wind speed exceeding the failure wind speed. A discrete distribution using this probability determines whether a lodging event occurs. It is assumed that if a lodging event occurs, the grain yield is reduced by 10% and the grain premium is lost. The probability of lodging occurring is shown in **Table 3.7**.

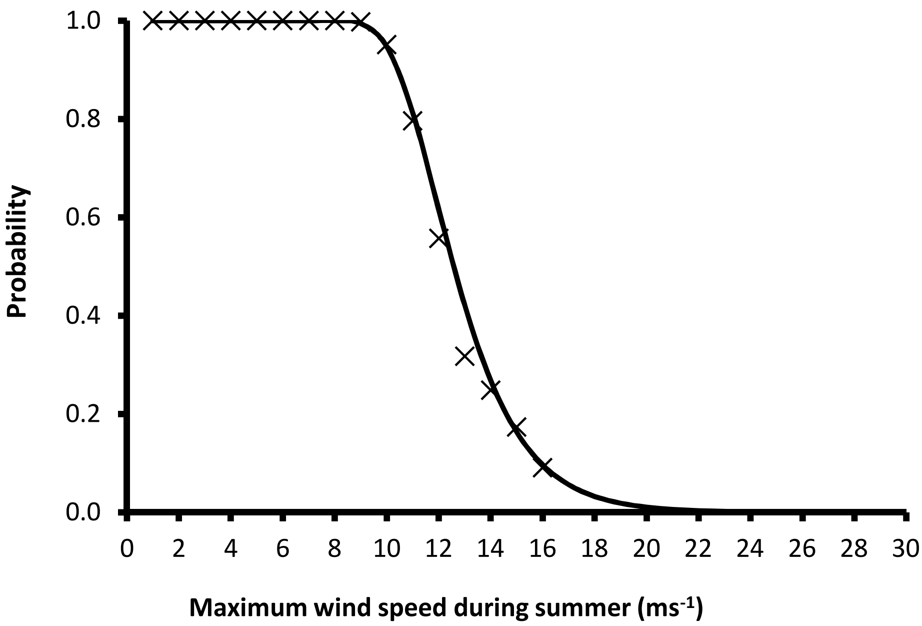


Figure 3.6: Gumbel wind distribution showing the probability of experiencing wind gusts at Sutton Bonington between mid-June and mid-August. From Berry et al. (2003c).

Table 3.7: Mean grain and straw yields, lodging risk and grain premium level for three years for the cultivars Cordiale, Grafton and Xi19. Grain premium level: level 0 is for feed wheats; level 1 is for biscuit milling quality (Nabim groups 2 and 3); level 2 is for bread milling quality (Nabim group 1).

Cultivar	Year	Grain	Straw	Lodging risk	Premium
Cordiale	2010	12.63	3.63	0	Level 1
	2011	10.85	3.40	0.95	Level 1
	2012	9.38	5.46	0.95	Level 1
Grafton	2010	9.38	2.78	0	Level 0
	2011	11.10	3.57	0.56	Level 0
	2012	9.38	5.61	0.95	Level 0
Xi19	2010	11.75	3.82	0	Level 2
	2011	11.89	4.00	1	Level 2
	2012	7.83	5.69	1	Level 2

3.5 Results

3.5.1 Straw breakeven prices

The fertiliser costs per tonne of straw were £13.65 and the contractor charges were £17.74, giving overall variable costs of £31.38 t^{-1} (**Fig. 3.7**). 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.

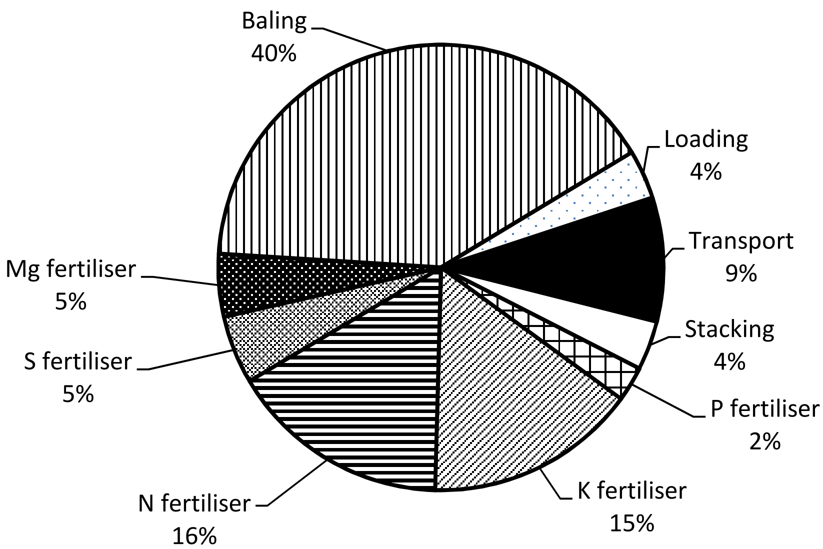


Figure 3.7: Percentage breakdown of the costs for baling, on-farm transport and replacement nutrients for 1 tonne of straw.

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 3.8**). 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 3.9**).

Of the farms surveyed as part of this project (see **Chapter 6**), and average area of wheat in East Midlands and the East of England is 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. 3.8**).

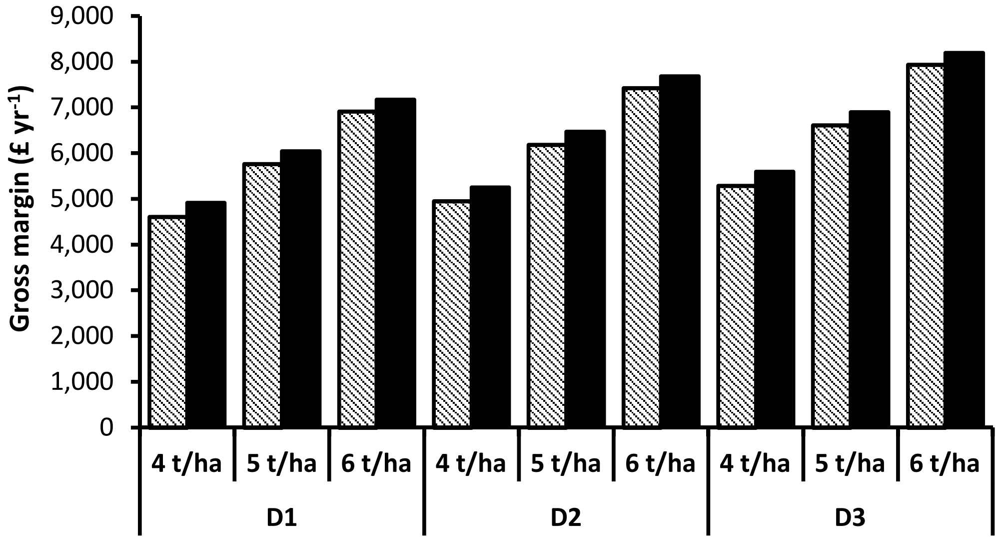


Figure 3.8: Annual gross margin of the nine hypothetical cultivars on a farm supplying 72 ha yr^{-1} of straw. Chopper: no chopper credit (diagonally-lined bars); with chopper credit (solid bars).

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 the 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} (£10.93). With the same farm as above this would equal an annual straw gross margin of £461.52 (£786.96 including the chopper credit).

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}.

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 3.8**). When chopper credit is taken into account the straw contributions to overall GMs increased to between 8.4% and 13.0% (**Table 3.9**). The increases in contribution are highest for the lower straw yields as the chopper credit is shared by fewer bales of straw.

Table 3.8: 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%

Table 3.9: Gross margins (GM) for straw and grain for the nine hypothetical cultivars and their contributions to the overall gross margins taking into account a chopper credit of £5.52 ha^{-1}.

Cultivar	Straw GM (£)		Grain GM (£)		Total GM (£ ha^{-1})	GM % Contribution	
	t^{-1}	ha^{-1}	t^{-1}	ha^{-1}		Straw	Grain
4D1	17.38	69.50	95.13	761	830.50	8.4%	91.6%
5D1	17.10	85.50	95.13	761	846.50	10.1%	89.9%
6D1	16.92	101.49	95.13	761	862.49	11.8%	88.2%
4D2	18.37	73.48	95.13	761	834.48	8.8%	91.2%
5D2	18.09	90.47	95.13	761	851.47	10.6%	89.4%
6D2	17.91	107.46	95.13	761	868.46	12.4%	87.6%
4D3	19.37	77.46	95.13	761	838.46	9.2%	90.8%
5D3	19.09	95.45	95.13	761	856.45	11.1%	88.9%
6D3	18.91	113.43	95.13	761	874.43	13.0%	87.0%

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.

This model assumes a constant grain yield. However, if trade-offs between grain and straw yield are considered here, the increases in GM from increasing straw yield is negated by a minor decrease in grain yield. For a crop with 4 t ha^{-1} straw and 8 t ha^{-1} grain, the increase in gross margin resulting from an increase in straw yield from 4 t ha^{-1} to 5 t ha^{-1} is negated by a reduction in grain yield of more than 0.17 t ha^{-1} (a 2% reduction). From 4 t ha^{-1} to 6 t ha^{-1}

this increase in gross margin is negated by a decrease of 0.34 t ha^{-1} (a 4.3% reduction).

For a straw price of £40 t^{-1} the straw GM is £8.62 t^{-1}. The straw GM is now 4.3-7.7% of the total wheat GM, depending on straw yield and digestibility. Increases in straw yield from 4 t ha^{-1} to 5 t ha^{-1} and 4 t ha^{-1} to 6 t ha^{-1} could be negated by decreases in grain yield of 0.09 t ha^{-1} and 0.18 t ha^{-1} (1.1% and 2.3% reductions in grain yield, respectively). Using the same straw supply assumptions as above, at £40 t^{-1} a farmer could get £2,481.25-4,585.88 yr^{-1}, depending on straw yield and digestibility.

For a straw price of £100 t^{-1} the straw GM is £68.62 t^{-1}. The straw GM is now 26.5-36.7% of the total wheat GM, depending on straw yield and digestibility. Increases in straw yield from 4 t ha^{-1} to 5 t ha^{-1} and 4 t ha^{-1} to 6 t ha^{-1} could be negated by decreases in grain yield of 0.72 t ha^{-1} and 1.44 t ha^{-1}, respectively (grain yield reductions of 9.0% and 18.0%, respectively). For a 4 t ha^{-1} straw yield, the straw GM is £274.48 ha^{-1}, which is still less than that of grain, even on a per tonne basis. Using the same straw supply assumptions as above, at £40 t^{-1} a farmer could get £19,761.25-31,801.88 yr^{-1}, depending on straw yield and digestibility.

3.5.1.1 Monte Carlo results

The straw variable costs ranged from £27.50-37.84 t^{-1} with an average of £31.72 t^{-1}. At a price of £47.38 t^{-1}, the GM ranged from £9.54-£19.88 t^{-1} with a mean of £15.67 t^{-1} (**Fig. 3.9**). For this price, or even a lower price of £40 t^{-1}, the value of the straw always exceeds the variable costs. GMs are higher when the chopper credit is included (an average of £16.59-17.05 t^{-1}, depending on the straw yield).

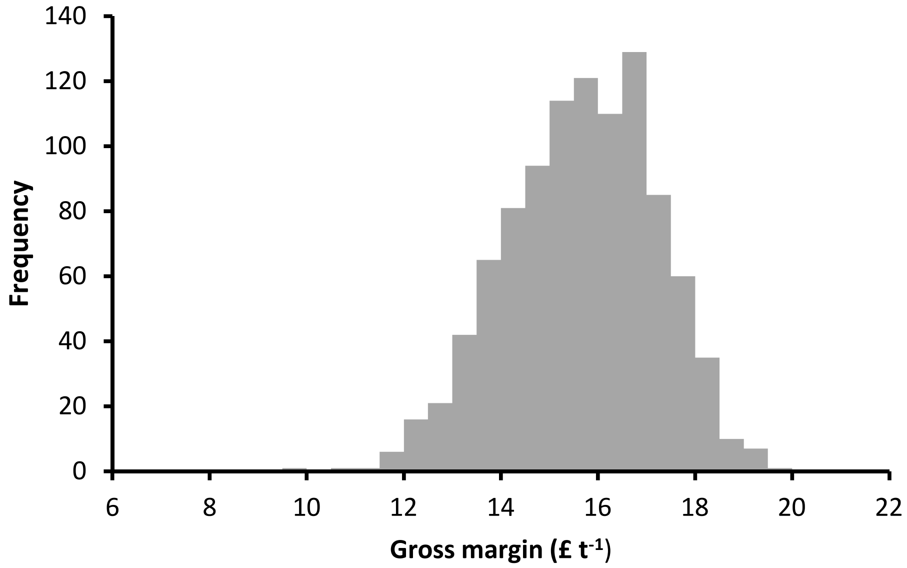


Figure 3.9: Straw gross margin outputs of the Monte Carlo simulation assuming a straw price of £47.38 t^{-1} and variable costs consisting of fertiliser and contractors fees.

3.5.2 Cultivar values

At straw prices of £40 t^{-1} and £47.38 t^{-1}, Cordiale has the highest GMs (**Fig. 3.10**, **Fig. 3.11**). At a straw price of £100 t^{-1} Xi19 has the highest GM of the three cultivars, slightly higher than Cordiale (**Fig. 3.12**). Grafton has the lowest GMs at all three straw prices.

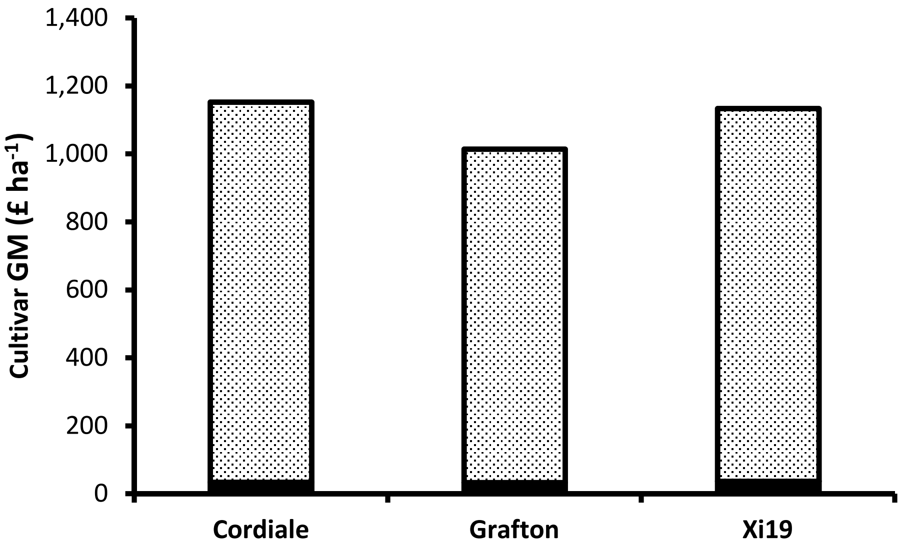


Figure 3.10: Straw and grain gross margins for a straw price of £40 t^{-1} for the three cultivars. Component: Grain (dotted bars); straw (solid bars).

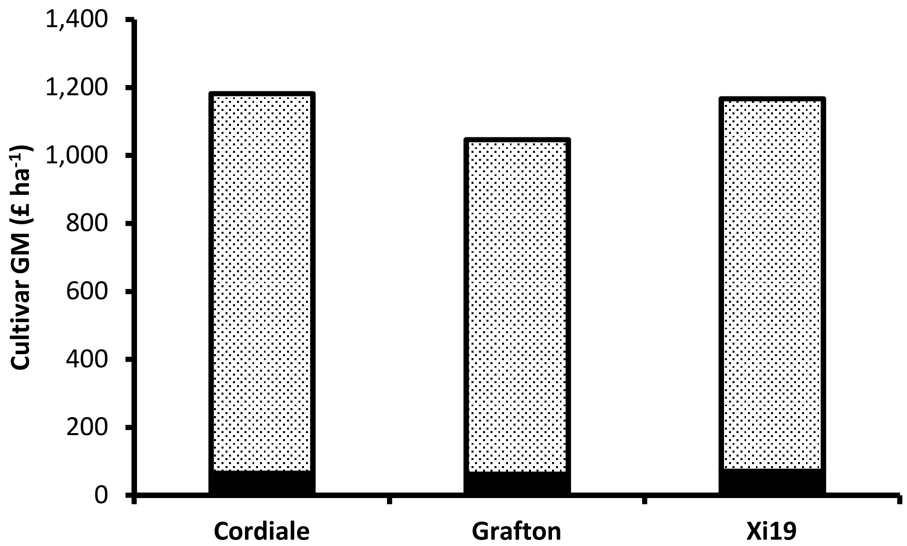


Figure 3.11: Straw and grain gross margins for a straw price of £47.38 t^{-1} for the three cultivars. Component: Grain (dotted bars); straw (solid bars).

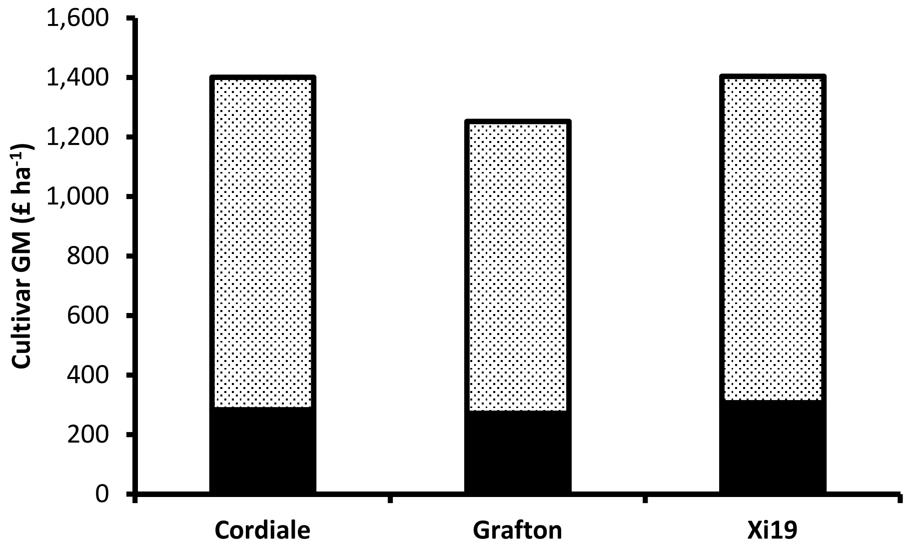


Figure 3.12: Straw and grain gross margins for a straw price of £100 t^{-1} for the three cultivars. Component: Grain (dotted bars); straw (solid bars).

When the digestibility premium is applied to the straw for Grafton, the overall increase in cultivar GM is small and does not impact on the price rankings of the cultivars. Applying the digestibility premium to Xi19 does not increase the overall GM above that of Cordiale when Cordiale's straw price remains at £47.38.

Xi19 showed the greatest range of results with the lowest overall GM, £632.26 ha^{-1}, which was £200 lower than the other cultivars. It also had the highest GM, £1,679.42, which was approximately £40 higher than Cordiale's highest GM. This is because it had the most variable grain yield. The low value resulted from it having the lowest grain yield (7.83 t ha^{-1} in 2013) of all samples. The high value represents a high grain yield but also a high grain premium price.

3.6 Discussion

3.6.1 Gross margins

Model 1 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 a lower contractors charge.

Value estimates differ in whether they include a credit for the saving from not using the straw chopper on the combine. The breakeven price was lower when the chopping credit was included but the extent of this depended on the straw yield.

MAFRA (2014) suggested a 15% premium for farmers, which would give a 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. (2012b) 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.

The variable costs calculated by model 2 suggest that there is variability in the straw GMs but even for a lower straw price of £40 t^{-1}, a gross margin is always gained. This means that if a fixed-contract for supply was used, the farmer would not be losing out if the fertiliser requirements were at the upper end of the estimates given for UK straw. However, these variable costs did not take account of the potential increases in fertiliser and contractor prices so it does not mean that in the future farmers would not be getting below the breakeven price if they had a fixed-contract. Glithero et al. (2013b) found that a large proportion of farmers were interested in straw supply contracts that had the straw price linked to the prices of P and K fertilisers.

At a price of £47.38 t^{-1}, the 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 gross margin 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.

The work in this chapter has attempted to shed light on the value of straw relative to grain for farmers. As will be seen in **Chapter 5**, understanding whether straw GMs or straw prices are drivers for production decisions can have influences on aspects such as the allocation of environmental burdens during the life cycle assessment of biofuels from wheat straw.

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.

3.6.2 Hypothetical cultivars

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.

3.6.3 Current cultivars

Cordiale was the most valuable cultivar for the lower straw prices. However, when the straw price was £100 t^{-1}, Xi19 was the most valuable cultivar to growers. This demonstrates a potential trade-off between grain and straw yields as Xi19 had the highest straw yields but a lower grain yield than Cordiale so it only had the highest value when straw prices were high. However, the differences in yields between these cultivars were minor, which meant that it required a very high price of £100 t^{-1} for the value rankings to switch.

The analysis was conducted with limited data meaning that it does not accurately predict the GMs of these cultivars. However, it does demonstrate a number of key points. As seen with model 1, the GM for straw is much lower than that for grain and, therefore, the overall GMs were dominated by the grain GM. This supports that cultivar selection should focus on the grain yield and quality. Including a digestibility premium did not alter the order of GM for the cultivars, which suggests that farmers would not select cultivars based on their digestibility. The GMs calculated for each cultivar demonstrates the importance of grain premiums and, therefore, grain quality in determining the overall cultivar GM. This, as mentioned earlier, adds another layer of complexity on determining the most valuable cultivar to farmers. To improve this assessment, a greater number of measurements are required and the relationship between the grain and straw for each cultivar need to be determined.

3.6.4 Fertiliser

This range of results demonstrates variability in the amounts and prices of fertilisers. Currently fertiliser prices are low enough that the current price of straw exceeds the breakeven price. However, there is uncertainty regarding future fertiliser prices and, although predicted to decrease in the short term (Baffes & Cosic, 2014), if they do increase then farmers may find that the prices offered for straw are close to the straw breakeven price. As straw contracts for power stations appear to be reasonably long-term with a fixed price, these changes in fertiliser prices could mean that farmers might end up making a loss.

With current fertiliser prices the exclusion of some types of fertiliser (e.g. N, Mg or S) from calculations of straw breakeven prices does not significantly influence the overall breakeven price. N fertiliser was 16% of the straw breakeven price and its inclusion increased the breakeven price by £5.02. As the straw breakeven price was still much lower than the straw price, excluding N from the analysis would not have led to the straw being sold for less than the value of the nutrients in it. However, if the price of N fertiliser were to increase, then its exclusion from these calculations would underestimate the value of the cultivars and could lead to then being sold below straw breakeven price.

The RB209 does not currently recommend S fertiliser to replace the S removed in the straw. The amount recommended in other sources costs approximately £1.56 t^{-1} straw. Likewise, Mg is also excluded from the RB209 recommendations but the amount of Mg fertiliser required per tonne straw costs approximately £1.42. The value is low suggesting that not including it will not have a large impact on GMs. The current fertiliser recommendations do not include Ca, even though this is exported in straw, but the cost of this is also likely to be low.

The models excluded the sources giving very high values as they were much higher than other values. If the values from Punter et al. (2004) were used, the variable costs now equal £47.60 t^{-1}, which is higher than the average price of straw.

3.6.5 Collection costs

Average contractor collection costs were used in the model but it is possible that lower costs could be achieved. With such a large amount of straw being supplied to a biofuel refinery, the savings might be achieved by investing in equipment and optimising the collection timing. A number of studies have investigated the optimisation of straw collection and have calculated the most appropriate amounts of equipment and workers to use.

Costs may also be reduced by the development of new equipment. Methods included greater bale compaction which reduces stacking time, storage requirements and allows greater loads to be transported (as straw loads tend to limited by volume rather than weight; Profi, 2009). Timeliness penalties could be reduced by speeding up the collection process by, for example, using large bale-picking trucks (a new model by KABB can hold 42 bales), and potential costs associated with soil compaction could be reduced by using larger tyres or controlled traffic (Profi, 2009).

3.6.6 Dual-purpose cultivars

Work with the hypothetical and real 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).

3.7 Conclusions

The main findings of this chapter are:

- The breakeven price for straw was calculated as £31.38 t^{-1}.

- GMs from selling straw are much smaller than grain; the proportions of GMs relative to price are also much lower for straw than grain.
- Increasing straw yield can increase overall farm GMs but because of the low GMs for straw the potential increase is relatively small. The result of increasing digestibility is very minor.
- Selling straw in the swath for the current average price covers the fertiliser costs for yields up to 4.4 t ha^{-1}.

Chapter 4: Straw transport costs

4.1 Introduction

This chapter examines how growing DPCs might influence transport distances and costs for straw haulage. A model is presented for determining how feedstock haulage distance and cost is influenced by changes in average straw yield and digestibility at the landscape level. The model is used to compare the hypothetical DPCs described in the previous chapter. These cultivars and their average transport distances are then used in the LCA chapter (**Chapter 5**).

4.2 Literature review

The transportation of feedstock is responsible for a large proportion of costs; therefore, 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). The aim of this experimental work is to calculate the average transport distances and costs for transporting straw from cultivars with different straw yields and digestibilities.

4.2.1 Key characteristics of feedstock transport systems

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).

The transportation component of the supply chain is dependent on the legal and infrastructural framework of the local area (Gold & Seuring, 2011). There are multiple transport modes available to transport feedstock (e.g. road, rail or sea), but the selection is dependent on the infrastructure and location of the supply area relative to plant (Miao et al., 2011). Either a single transportation mode or a combination of two or more transportation modes can be used, with the likelihood of multiple modes increasing as feedstock demand increases. The transport mode choice has an influence on the overall costs of biofuel production (Mahmudi & Flynn, 2006).

The road infrastructure in Europe is much larger than that of rail or barge, allowing access to remote rural areas where the feedstock is produced, as well as having high capacity (Gonzales et al., 2013). However, truck transport costs per tonne per km tend to be higher than rail or barge. Thus, truck transport is usually used for relatively short distances (<100 km) when flexibility is required to access multiple production sites and when train and ship infrastructure is not present (Hamelinck, et al., 2005). In the UK, the infrastructure is suited to road transport and crop residues are transported by truck (e.g. straw collection for Ely straw-fired power station; Newman, 2003). The road properties have a large influence on the transport characteristics (Möller & Nielsen, 2007).

Feedstock transportation is responsible for a large proportion of the environmental and social impacts of the biomass supply chain; these impacts include traffic generation, vehicle emissions, vehicle noise, visual intrusion, water pollution and the health and safety of workers and the public (Allen et al., 1996). Gaining planning permission requires that these impacts are minimised. This could be achieved through the choice of location for the biorefinery or utilising specific measures to limit these impacts. For example, congestion caused by the delivery of feedstock could cause community resistance (Bai et al., 2011). Reducing disruption to the local community could take the form of restricting haulage routes, which would have an influence on travel distances and times. For example, in seeking planning permission for construction of the straw-fired Brigg bioenergy plant, the authors state that the trucks would be restricted in the routes that they can take, limited to roads that are suitable for HGVs and avoiding traffic impact on villages and Brigg town centre (Anon, 2009).

4.2.2 Delivery 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).

Road haulage costs are dependent on a number of variables. One of the main variables is the time taken to carry out the transport operation, which is divided into travel time and non-travel time. Other variables are the distance and the vehicle capacity.

- Travel time: This is a function of distance and speed, which are a result of the road properties (Möller & Nielsen, 2007). The distance travelled depends on the demand for feedstock, the supply density of feedstock, as well as the road infrastructure. An important value here is road tortuosity, which is the ratio of the straight-line distance to the actual road distance. Speed is determined by factors such as vehicle type, road laws, the types of road infrastructure available and the scheduling of personnel and vehicles (Möller & Nielsen, 2007). Thus these travel times are a result of the infrastructure and supply characteristics of the area supplying feedstock.
- Non-travel time: This includes the time spent during loading and unloading, as well as any intermediate processing (Möller & Nielsen, 2007). Unlike travel time, these time costs are independent of location and remain approximately constant regardless of distance.
- Distance: In terms of haulage costs, travel distance mainly affects tyre and engine wear and fuel consumption, whilst non-travel and travel time affect mainly the proportion of depreciation, insurance,

maintenance and labour allocated to that particular journey (Rentizelas et al., 2009).

- The amount of feedstock that can be transported in the vehicle is a key cost variable (Hamelinck et al., 2005); this is dependent on the bulk density of the material and the volumetric or weight capacity of the vehicle, whichever is limiting.

Transport costs vary in how they are included in models; their design depends on the overall focus of the models. Some papers assume fixed transport parameters; this could be for all types of feedstock, such as Giarola et al. (2012) who use a standard value €23.2 (£19.32) t^{-1} for all biomass, or a different value for each feedstock (e.g. Slade et al., 2009). Other models have variable transport parameters and, therefore, calculate distances and time based on the input parameters (e.g. Huang et al., 2009). These costs often take the form of distance-fixed costs and distance-variable costs; distance-variable costs depend on travel time and distance whilst distance-fixed costs depend on the non-travel time and the operations, such as loading and unloading, that are allocated to the transport stage. Huang et al. (2009) calculated transport costs by assuming a distance-variable hauling cost of \$0.11 (£0.07) odt^{-1} km^{-1} and a distance-fixed cost of \$7.61 (£4.66) odt^{-1} for corn stover. Other studies combine the variable and fixed costs into a single value; for example Akgul et al. (2012) estimated transport costs of £0.47 t^{-1} km^{-1} for delivering biomass in the UK.

There are few studies investigating biomass transportation costs in the UK and very little data is available on industrial-scale straw transportation costs. Slade et al. (2009) assumed a cost of US$14.9 (£9.12) odt^{-1} for transporting baled straw assuming a 50 km trip, which is much lower than Akgul et al.'s (2012) estimated transport costs of £0.47 t^{-1} km^{-1} for delivering biomass in the UK. Other feedstocks have been considered: Bauen et al. (2010) calculated distance-fixed costs as £1.81 odt^{-1} and £4.28 odt^{-1} and distance-variable costs as £0.17 odt^{-1} km^{-1} and £0.27 odt^{-1} km^{-1} for short rotation coppice and baled Miscanthus, respectively, for delivery in the UK.

Comprehensive straw transportation cost estimates appear to be unavailable in the UK, making it difficult to include accurate data in models. Some models base the transportation costs on other studies (e.g. Slade et al., 2009; Akgul et al., 2012; Littlewood et al., 2013), some of which are transport rates for other countries and biomass types. Whilst others base travel costs on commercial freight costings; for example, Bauen et al. (2010) based their haulage costs on data produced by the Road Haulage Association. Roger & Brammer (2009) used operating costs and average use figures to calculate a transport rate based on biomass haulage characteristics, arguing that as the majority of feedstock haulage will occur on slower rural roads, and a large proportion of time is required for unloading and loading, commercial freight costings are not appropriate cost structures. Feedstock collection is often by specialist haulage companies (e.g. Anglian Straw Ltd., who collect straw for Ely straw-fired power station, Newman, 2003) with expertise in feedstock collection, which allows them to provide higher efficiencies of operation. This is likely to result in a different cost structure.

Most transport models calculate costs based on a simple distance rate yet Rogers & Brammer (2009) suggest using a cost per transport zone approach. This is because time costs, in particular those resulting from loading and unloading, are more important. Thus organising collections based on the number of round-trips that can be undertaken in a day is considered more important than the actual distances travelled. In other words, maximising the utilisation of the equipment is more important than reducing overall distance.

4.2.3 Modelling straw collection

Biomass supply chains have been modelled extensively (see Gold & Seuring, 2011, and Sharma et al., 2013, for detailed reviews of the models used). Transport models often take the form of sub-models in models of the complete biofuel supply chain. The transport components of these models help optimise location and feedstock demand.

Biomass feedstock supply chain models have considered many different aspects of supply with the purpose of determining optimal configurations for the feedstock supply chain (Miao et al. 2012). Many of the studies focus on specific regions, using either region-specific data or assumed data (Sharma et al., 2013). The majority of models have focused on the US with only a few studies considering the situation in the UK (e.g. Rogers & Brammer, 2009; Akgul et al., 2012).

The majority of the models cover the complete supply chain but have a focus on a particular aspect. Aspects considered include: different logistics equipment configurations (e.g. Thorsell et al., 2004), the influence of storage options (e.g. Rentizelas et al., 2009), feedstock moisture content throughout the supply chain (e.g. Sokhansanj et al., 2006), feedstock densification and transport mode (e.g. Gonzales et al., 2013) and traffic flows and congestion (e.g. Bai, et al., 2011).

The transport stage is modelled in varying levels of detail. Yu et al. (2009) define three main methods for modelling the transport stage: *type 1* are simple continuous models (e.g. Overend, 1982); *type 2* are discrete models with a defined road network (e.g. Sokhansanj et al., 2006); and *type 3* are complete discrete models incorporating geographical information systems (e.g. Skog et al., 2008). Type 1 models assume an idealised system, for example an even distribution of feedstock within a circular area, and for that reason are only suitable for investigating general trends rather than for determining logistics characteristics for specific locations. Type 1 models are often used due to limitations in the data available for producing type 2 and 3 models. They also tend to be used as general models rather than assessments of specific locations unlike GIS studies, which require a specific location.

Transport models demonstrate the importance of locating the biorefinery in close proximity to large supplies of feedstock and in areas with a good transport network. However, achieving both is not always possible; therefore, optimising site location to minimise transport costs requires a potential trade-off between these factors (Bai et al., 2011). As transport system configurations are determined by the local road laws and existing road infrastructure there is limited scope to reduce costs (Hess et al., 2007); however, increasing truck capacity and optimising the journeys and deliveries offer a means to increase efficiency.

Calculating transport costs is vital when it comes to the economic optimisation of refinery size. One of the main considerations when determining the economic optimal plant size is the trade-off between the economy of scale (i.e. in general, the larger the plant the lower the processing costs per unit produced) and the costs of transporting feedstock, which increase with feedstock demand as biomass needs to be sourced from greater distances (Kaylen et al., 2000; Rosburg & Miranowski, 2011). The optimum size of the plant increases with decreasing transportation costs and higher biomass production per unit area surrounding the plant (Searcy et al., 2007). Determining the relationship between feedstock demand and transportation costs is important, however, the relationship is unclear. Kaylen et al. (2000) suggest that as plant size increases, transportation cost will increase at an exponential rate, whereas Huang et al. (2009) suggest that transportation costs will increase but at a decreasing rate. A large proportion of biomass supply chain models approach it as an optimisation of refinery size (e.g. Huang et al., 2009; Leboreiro & Hilaly, 2011).

Various studies have compared feedstocks from an economic perspective. Huang et al. (2009) considered increasing feedstock supply and found that ethanol production costs decrease with increasing crop availability, but the magnitude of this decrease gets less as crop availability increases. Morrow et al. (2006) examined the effect of switchgrass yield on feedstock transport and found that increasing yield allowed the biorefineries to source adequate feedstock closer, resulting in a reduction in transport distances and costs, and an overall reduction in biofuel cost. Hamelinck et al. (2005), in modelling optimal refinery size for biofuel from energy crops, found increasing yields decreased the transport distances, thus allowing a greater economically feasible feedstock demand. Huang et al. (2009) demonstrated the importance of feedstock chemical composition to bioethanol production by comparing corn stover, switchgrass, aspen, and hybrid poplar; they found that ethanol yield and excess electricity generated varied between species, but the highest ethanol yielding species (aspen wood) also produced the lowest excess electricity.

Increasing straw yields will, therefore, reduce the distance that feedstock will need to be transported. Increasing digestibility will also reduce the distances travelled, and moreover reduce the total amount of feedstock. The importance of these two factors on decreasing overall costs depends on the relative price of straw haulage compared to other costs. These might result in processors being willing to travel further to collect feedstock of higher digestibility. This would be relevant to farmers because those further away from the processing plant might only have access to the market if they grow cultivars that have high digestibility. Ultimately, this would depend on the costs of the extra distance to collect feedstock, relative to the additional ethanol yield they obtained from that feedstock. This could, therefore, have an influence on farmer decision making.

4.3 Chapter aims

The aims of the experimental work presented in this chapter:

- Determine how straw yield influences average collection distances and costs.
- Determine how straw digestibility influences average collection distances and costs.
- Determine how these distances and costs vary with annual feedstock demand.
- Use sensitivity analysis to consider the impact of other variables (proportion of land supplying straw, the tortuosity factor) on these distances and costs.
- Determine how increases in digestibility affect the number of deliveries.

4.4 Methodology

4.4.1 Hypothetical cultivars

These cultivars were described in **Chapter 3**.

4.4.2 Feedstock demand

As the capacities of future UK biorefineries are unknown, three feedstock demands will be modelled: 250,000 tonnes yr^{-1}, which matches the demand for the bioenergy plants currently in construction in the UK (Eco2 UK's Brigg and Sleaford biomass-burning power stations), 750,000 tonnes yr^{-1}, which matches the demand modelled by Borrion et al. (2012b), and an intermediate demand of 500,000 tonnes yr^{-1}. For a demand of 250,000 t yr^{-1}, 500,000 t yr^{-1} and 750,000 t yr^{-1} respective annual ethanol production capacities are 98.4 ML, 196.9 ML and 295.3 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 amounts of straw at 16% MC for each digestibility level required for each demand are given in **Table 4.1**. In the current model it is assumed that no material is lost between the baling of the straw and delivery of the straw at the biorefinery.

Table 4.1: Feedstock at 16% MC and three digestibilities required to meet annual feedstock demand; and feedstock (16% MC) requirement for the production of a litre of ethanol. Where D2 gives an additional 2.5% of ethanol yield above D1, and D3 gives an additional ethanol yield of 5% above D1.

Digestion level	**Feedstock demand (t yr^{-1})**			**kg straw L^{-1}**
	250,000	**500,000**	**750,000**	
D1	297,619	595,238	892,857	3.024
D2	290,360	580,720	871,080	2.950
D3	283,447	566,893	850,340	2.880

4.4.3 Model

The transport costs are calculated using a *type 1 simple continuous* transport model based on examples by Overend (1982), Huang et al. (2009) and Leboreiro & Hilaly (2011).

4.4.3.1 Supply area

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. 4.1**).

$$R = \left(\frac{F}{\pi S Y}\right)^{0.5} \qquad \textbf{Eq. 4.1}$$

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. Variability in *S* will be investigated further with sensitivity analysis.

4.4.3.2 Average haul distance

The average haul distance is calculated using **Eq. 4.2** 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.

$$D = \frac{4}{3}R \times \tau \qquad \textbf{Eq. 4.2}$$

Where: R = radius of total supply; D = average haulage distance; τ = tortuosity factor

The tortuosity factor (τ) 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). Various tortuosity factors have been used in studies of biofuel logistics. The actual value used will depend on the location (Overend, 1982). However, values are currently not available for most locations and, therefore, the actual values chosen for models tend to be based on assumptions about the area. A range of values have been used: Perlack & Turhollow (2003) assumed a τ *of* 1.3 for the US; Stephen et al. (2010) assumed a τ of 1.4 for the Canadian Prairie; and Rentizelas et al. (2009) assumed a τ of $\sqrt{2}$ (approximately 1.414) for rural road networks in Greece. The $\sqrt{2}$ value used by Rentizelas et al. (2009) matches very closely the value of 1.417 that Boscoe et al. (2012) found when considering τ for distances to hospitals in the USA (66,000 origins and 5,000 destinations). In assessing road networks in the Western Australian wheat belt, Yu (2009) found that τ increases slightly as feedstock collection distance increases until reaching a steady state at 40 km.

GPS tracking of trucks in the US during corn stover transport system found a range of values but an average τ of 1.48 (Gutesa et al., 2012). However, longer distances were found to occur because drivers became lost or took an inefficient path to the delivery location due to traffic or roadworks. This is something that must be considered when calculating the actual road distance; even with planning and GPS, there is still the possibility of the most efficient route not being taken. There is also the consideration of other restrictions on the road network, such as weight- or height-restricted bridges limiting HGV use, and restrictions through local communities, which could increase the τ, as well as temporary restrictions such as road works, which can cause longer journey distances and/or journey times. There is also the possibility that the shortest distance does not give the quickest journey time due to the speed limits on the roads (King & Cole, 1968).

There is limited data available for English roads; one study took place in the 1960s where the majority of roads had a τ of 1.2 to 1.6 (Cole & King, 1968). The major roads network will have increased since then. In the UK, Azgul et al. (2012) assumed a τ of 1.4 for the collection of multiple feedstock types and Bauen et al. (2010) assumed a τ of 1.6 for the collection of Miscanthus and short rotation coppice willow. Bridgwater et al. (2002) assumed a τ of $\sqrt{2}$ for UK roads for the delivery of wood chips.

In the current study a value of 1.5 is used for τ. It is assumed that τ does not change as the average straight line distance increases. The impact of this choice of τ will be considered in the sensitivity analysis.

4.4.3.3 Number of deliveries

The number of deliveries required will vary with the feedstock demand; as increasing digestibility reduces the amount of feedstock required this will lead to fewer deliveries. As part of the model, the numbers of deliveries are calculated for the different digestibilities of the theoretical cultivars.

Due to the low bulk density of straw, the volumetric capacity of trucks will be exceeded before weight capacity and, therefore, the trucks will not be running at full load. Trucks supplying Ely have a volumetric capacity of 36 bales (approximately 18 tonnes; Newman, 2003), although it is suggested that a load of 19.8 tonnes is possible by increasing bale density (36 Hesston bales of approximately 550 kg; Anon, n.d.). The model will use the value of 18 tonnes; however, the higher load will be considered to see how capacity influences transport costs. It is assumed that all trucks are fully loaded and, therefore, the total straw tonnage is divided by 18 to derive the number of truck deliveries.

The 2012 harvest demonstrated the difficulties of collecting straw during unfavourable weather (see **Chapter 6**). Some supply chain analyses account for unsuccessful straw collection trips but this will not be included in the study; instead, it is assumed that all collections are successful.

4.4.3.4 Delivery costs

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. It is assumed there are no additional costs (e.g. road toll charges).

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).

These data is used to calculate 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.

4.4.3.5 Sensitivity analysis

As there is uncertainty regarding some of the key variables in the model, sensitivity analysis of key parameters is used to assess how this uncertainty might impact upon the results.

The influence of S on overall transport distances is assessed. Multiple values for S will be used (5% to 15% with 0.5% increments) for each experimental cultivar. The sensitivity analysis is then used to consider how much S would have to increase to match the decreases in distance that result from an increase in straw yield or digestibility, if the straw yield was to remain at 4 t ha^{-1}.

As exact values for τ are unavailable, sensitivity analysis is used to consider the impact of the choice of τ on the model results and the conclusions drawn from them. Two additional values for τ were compared: a lower value of 1.3 and a higher value of 1.7.

4.5 Results

4.5.1 Transport distances

Increasing straw yield from 4 t ha^{-1} to 5 t ha^{-1} and 6 t ha^{-1} reduced 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. 4.1**). 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}.

When the three feedstock demands are compared there is a nonlinear response in transport distance to increases in feedstock demand (**Fig. 4.2**), with further increases in feedstock demand having diminishing increases in collection distance, as found by Huang et al. (2009).

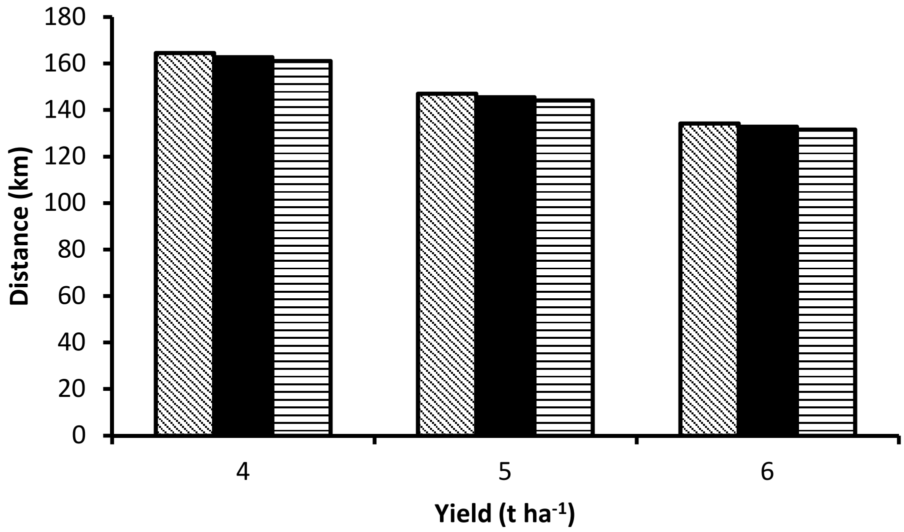


Figure 4.1: The average two-way haulage distance for the nine cultivars for feedstock demand of 500,000 t yr^{-1}. Digestibility: D1 (diagonally-lined bars); D2 (solid bars); D3 (horizontally-lined bars).

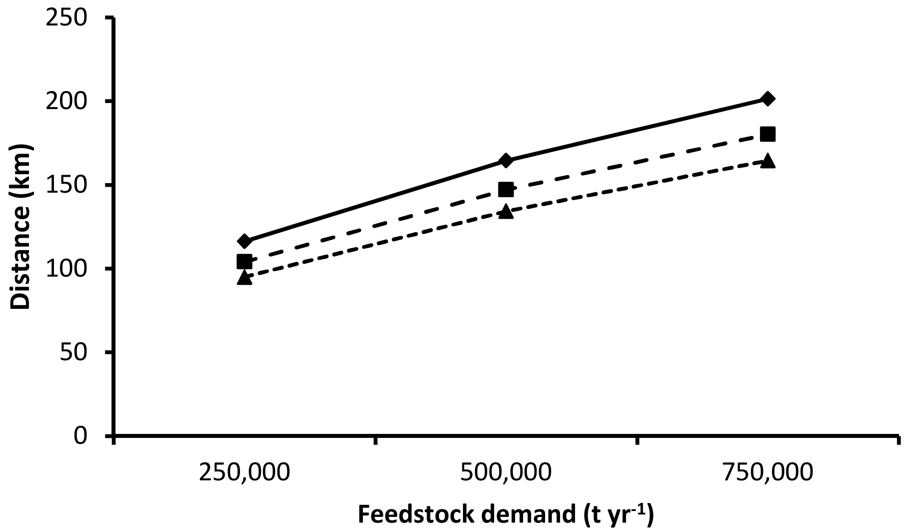


Figure 4.2: The average two-way haulage distance for the three straw yields for three annual feedstock demands. Straw yield: 4 t ha^{-1} (diamond data points); 5 t ha^{-1} (square-data points); 6 t ha^{-1} (triangle data points). Digestibility is D1 for all cultivars.

4.5.2 Number of deliveries

For the 250,000 tonne demand, the number of collections for the three digestibilities are 16,534 (D1), 16,131 (D2) and 15,747(D3). This is equal to a reduction of 2.43% and 4.76% in the number of collections for D2 and D3, respectively, compared to D1. Increasing truck loading from 18 t to 19.8 t decreases the number of deliveries by 8.16%.

4.5.3 Delivery costs

The costs for delivering 1 tonne of straw, at the midpoint demand (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. 4.3**).

The costs for delivering feedstock for 1,000 litres bioethanol, at the midpoint demand (500,000 t yr^{-1}) and baseline digestibility (D1) are £41.87, £38.65 and £36.28 for yields of 4, 5 and 6 t ha^{-1}, respectively (**Fig. 4.4**). Increasing yield from 4 t ha^{-1} to 6 t ha^{-1} leads to a 13.35% reduction in costs. For a feedstock demand of 250,000 t yr^{-1} this translates to a 12.00% reduction whilst at the 750,000 demand this is a 14.05% reduction, suggesting greater cost savings from increasing yields at higher feedstock demands.

At the midpoint demand and yield (500,000 t yr^{-1}; 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 (**Fig. 4.4**). Increasing digestibility from D1 to D3 leads to a 6.34% reduction in costs. For a feedstock demand of 250,000 t yr^{-1} this translates to a reduction of 6.20% whilst at the 750,000 t yr^{-1} demand this is a 6.47% reduction. As with yield, the extent of this reduction increases as demand increases because the distance-fixed costs (i.e. loading and unloading costs) become proportionally smaller allowing the distance-variable costs to have a greater influence on overall 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 17.41%, 18.84% and 19.58% for feedstock demands of 250,000 t yr^{-1}, 500,000 t yr^{-1} and 750,000 t yr^{-1}, respectively (see **Table 4.2**).

These results are for a load of 18 t; increasing the straw load to 19.8 t reduces costs by approximately 9.10% for all cultivars and feedstock demands.

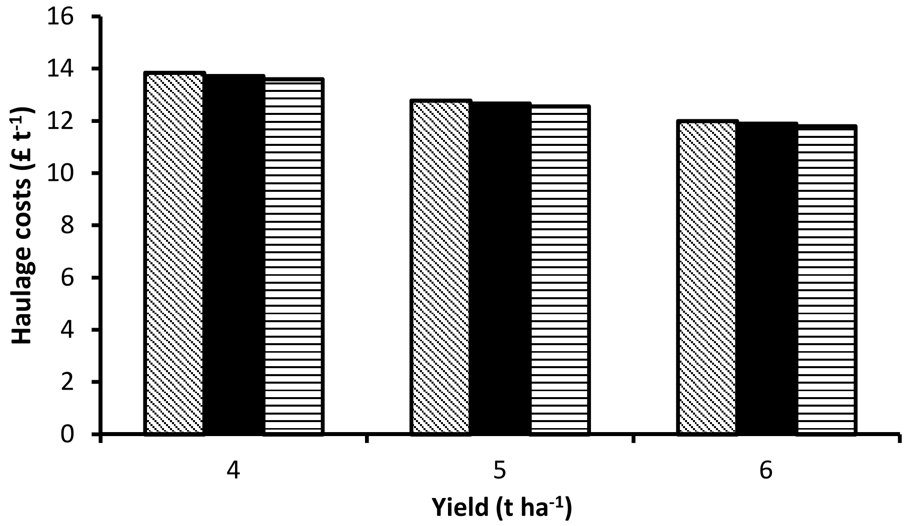


Figure 4.3: The haulage costs for the nine cultivars for feedstock demand of 500,000 t yr^{-1}. Digestibility: D1 (diagonally-lined bars); D2 (solid bars); D3 (horizontally-lined bars).

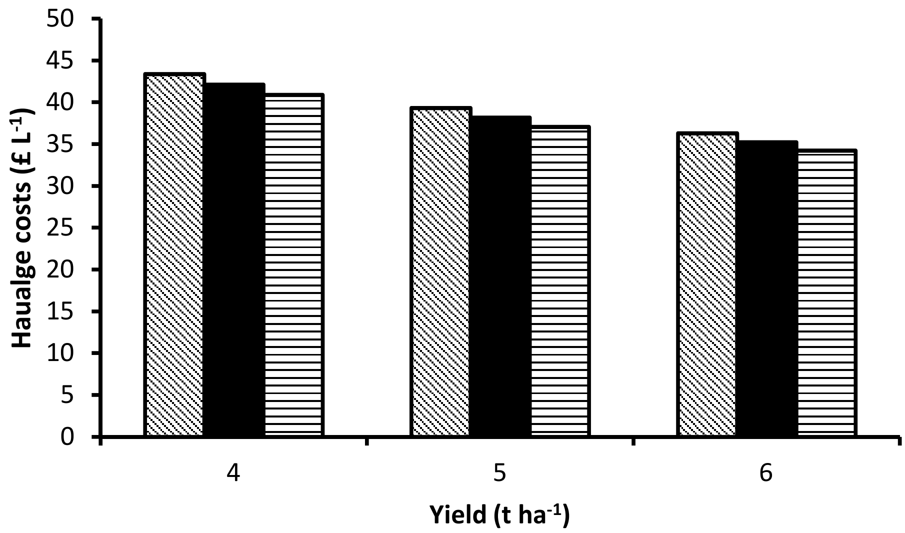


Figure 4.4: The haulage costs for the straw mass required to produce 1000 L bioethanol for the nine cultivars for feedstock demand of 500,000 t yr^{-1}. Digestibility: D1 (diagonally-lined bars); D2 (solid bars); D3 (horizontally-lined bars).

4.5.4 Sensitivity analysis

Increasing the proportion of land supplying straw (*S*) in the supply area decreases transport distances and costs (**Fig. 4.5**). To achieve equivalent decreases in transport distances and costs that equate to increasing yield from 4 t ha^{-1} to 5 t ha^{-1} and 6 t ha^{-1}, *S* must be increased from 7% (at 4 t ha^{-1}) to 8.75% and 10.5%, respectively. To achieve equivalent *transport distance reductions* from increasing digestibility of a 4 t ha^{-1} wheat straw cultivar from D1 to D2 and D3, *S* must be increased from 7% to 7.18% and 7.35%, respectively. However, to achieve equivalent *delivery cost reductions* from increasing digestibility from the D1 to D2 and D3, **S** must be increased from 7% at 4 t ha^{-1} to 7.69% and 8.43%, respectively.

Changing *S* does not change the percentage difference in the *transport distances* between the nine cultivars. For example, for the D1 cultivars the transport distances for the 6 t ha^{-1} cultivar is 18.4% lower than for the 4 t ha^{-1} cultivar for any value of *S*. However, percentage differences in *haulage costs* between cultivars do change with *S*, due to a change in ratio of fixed and variable haulage costs. Given *S* at 5% (500,000 t yr^{-1} demand, D1) the percentage difference in collection cost for feedstock for 1000 L ethanol between the 4 t ha^{-1} and 6 t ha^{-1} yielding cultivars is 13.93%, whilst given *S* at 15% (500,000 t yr^{-1} demand, D1) the percentage difference between the 4 t ha^{-1} and 6 t ha^{-1} yielding cultivars decreases to 11.85% (**Table 4.2**). The difference between highest and lowest digestibility cultivars also decreases with increasing values of *S*.

The tortuosity factor (τ) shows a linear relationship with transport distance and, as with variation in *S*, varying τ does not vary the percentage differences in the average *transport distances* between the cultivars but it does influence the percentage differences in *delivery costs* between the cultivars (**Table 4.3**). For example, for a 5 t ha^{-1} straw yield cultivar with D1 digestibility at a 500,000 t yr^{-1} feedstock demand, lowering τ to 1.3 reduces costs by 9.40%, but increases them by 9.40% when increasing τ from 1.5 to 1.7 (**Fig. 4.6**). However, for a D1 cultivar with yields of 4 t ha^{-1}, increasing τ to 1.7 increases costs by 9.70% whilst for a D3 cultivar with yields of 6 t ha^{-1}, increasing τ to 1.7 increases costs by 9.07%. The extent of these differences varies with feedstock demand; the increase in the transport costs of a cultivar with a 5 t ha^{-1} straw yield and D1 as τ is increased from 1.5 to 1.7 are 8.38% at a feedstock demand of 250,000 t yr^{-1} but 9.94% at a feedstock demand of 750,000 t yr^{-1}.

As with *S*, changing τ does not influence the percentage differences in transport distances between the cultivars. However, the percentage differences in haulage costs do change due to a change in ratio of distance-fixed and distance-variable costs. At the 1.3 = τ (F = 500,000 t yr^{-1}, D1) the percentage difference in transport costs for feedstock for 1000 L ethanol between the 4 t ha^{-1} and 6 t ha^{-1} yielding cultivars is 12.81%, whilst at τ = 1.7 (F = 500,000 t yr^{-1}, D1) the percentage difference between the 4 t ha^{-1} and 6 t ha^{-1} yielding cultivars increases to 13.79%. The difference between highest and lowest digestibility cultivars also increases with increasing values of τ.

Table 4.2: Costs (£) for transporting feedstock to produce 1000 L ethanol for three supply proportions (*S*) and for different feedstock demands. Numbers in parenthesis are the percentage differences in costs for transporting feedstock for 1,000 L ethanol relative to a cultivar with a 4 t ha-1 yield and D1 digestibility. τ = 1.5.

Yield	Digestibility	Demand = 250,000 t yr^{-1}			Demand = 500,000 t yr^{-1}			Demand = 750,000 t yr^{-1}		
		S = 5%	S = 7%	S = 15%	S = 5%	S = 7%	S = 15%	S = 5%	S = 7%	S = 15%
4	D1	36.89	32.95	26.12	47.45	41.87	32.22	55.55	48.72	36.89
	D2	35.69	31.88	25.31	45.86	40.48	31.18	53.66	47.08	35.69
		-3.30%	-3.20%	-3.10%	-3.40%	-3.30%	-3.20%	-3.40%	-3.40%	-3.30%
	D3	34.55	30.88	24.54	44.36	39.18	30.2	51.89	45.54	34.55
		-6.30%	-6.30%	-6.10%	-6.50%	-6.40%	-6.20%	-6.60%	-6.50%	-6.30%
5	D1	34.2	30.67	24.57	43.65	38.65	30.02	50.89	44.78	34.2
		-7.30%	-6.90%	-5.90%	-8.00%	-7.70%	-6.80%	-8.40%	-8.10%	-7.30%
	D2	33.09	29.69	23.81	42.19	37.38	29.06	49.17	43.28	33.09
		-10.30%	-9.90%	-8.90%	-11.10%	-10.70%	-9.80%	-11.50%	-11.20%	-10.30%
	D3	32.05	28.77	23.1	40.83	36.19	28.16	47.56	41.88	32.05
		-13.10%	-12.70%	-11.60%	-14.00%	-13.60%	-12.60%	-14.40%	-14.00%	-13.10%
6	D1	32.22	28.99	23.42	40.84	36.28	28.4	47.45	41.87	32.22
		-12.70%	-12.00%	-10.30%	-13.90%	-13.40%	-11.90%	-14.60%	-14.10%	-12.70%
	D2	31.18	28.07	22.7	39.48	35.09	27.5	45.86	40.48	31.18
		-15.50%	-14.80%	-13.10%	-16.80%	-16.20%	-14.60%	-17.40%	-16.90%	-15.50%
	D3	30.2	27.21	22.03	38.22	33.98	26.66	44.36	39.18	30.2
		-18.10%	-17.40%	-15.70%	-19.50%	-18.80%	-17.30%	-20.10%	-19.60%	-18.10%

Table 4.3: Costs (£) for transporting feedstock to produce 1000 L ethanol for different road tortuosity factors (τ) and for different feedstock demands. Numbers in parenthesis are the percentage differences in costs for transporting feedstock for 1,000 L ethanol relative to a cultivar with a 4 t ha^{-1} yield and D1 digestibility. S = 7%.

Yield	Digestibility	Demand = 250,000 t yr^{-1}			Demand = 500,000 t yr^{-1}			Demand = 750,000 t yr^{-1}		
		τ = 1.3	τ = 1.5	τ = 1.7	τ = 1.3	τ = 1.5	τ = 1.7	τ = 1.3	τ = 1.5	τ = 1.7
4	D1	30.07	32.95	35.82	37.81	41.87	45.93	43.74	48.72	53.69
	D2	29.12	31.88	34.65	36.57	40.48	44.39	42.28	47.08	51.87
		-3.20%	-3.20%	-3.30%	-3.30%	-3.30%	-3.40%	-3.30%	-3.40%	-3.40%
	D3	28.21	30.88	33.55	35.4	39.18	42.95	40.92	45.54	50.16
		-6.20%	-6.30%	-6.30%	-6.40%	-6.40%	-6.50%	-6.40%	-6.50%	-6.60%
5	D1	28.1	30.67	33.24	35.02	38.65	42.29	40.33	44.78	49.23
		-6.60%	-6.90%	-7.20%	-7.40%	-7.70%	-7.90%	-7.80%	-8.10%	-8.30%
	D2	27.22	29.69	32.17	33.88	37.38	40.88	38.99	43.28	47.57
		-9.50%	-9.90%	-10.20%	-10.40%	-10.70%	-11.00%	-10.90%	-11.20%	-11.40%
	D3	26.38	28.77	31.16	32.81	36.19	39.56	37.74	41.88	46.01
		-12.30%	-12.70%	-13.00%	-13.20%	-13.60%	-13.90%	-13.70%	-14.00%	-14.30%
6	D1	26.65	28.99	31.34	32.96	36.28	39.6	37.81	41.87	45.93
		-11.40%	-12.00%	-12.50%	-12.80%	-13.40%	-13.80%	-13.60%	-14.10%	-14.50%
	D2	25.81	28.07	30.33	31.9	35.09	38.9	36.57	40.48	44.39
		-14.20%	-14.80%	-15.30%	-15.60%	-16.20%	-15.30%	-16.40%	-16.90%	-17.30%
	D3	25.03	27.21	29.39	30.9	33.98	37.06	35.4	39.18	42.95
		-16.80%	-17.40%	-17.90%	-18.30%	-18.80%	-19.30%	-19.10%	-19.60%	-20.00%

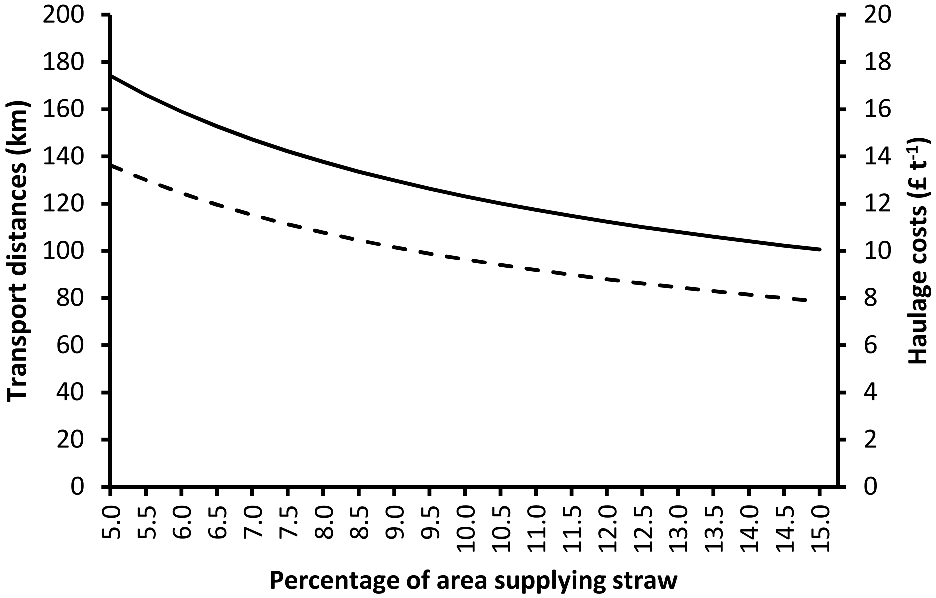


Figure 4.5: Transport distances and haulage costs for the mass of straw required to produce 1,000 L bioethanol (feedstock demand of 500,000 t yr^{-1}, 5 t ha^{-1} yield, D1) as the percentage of land supplying straw increases from 5% to 15%. Lines: haulage distance (solid line); haulage costs (dashed line).

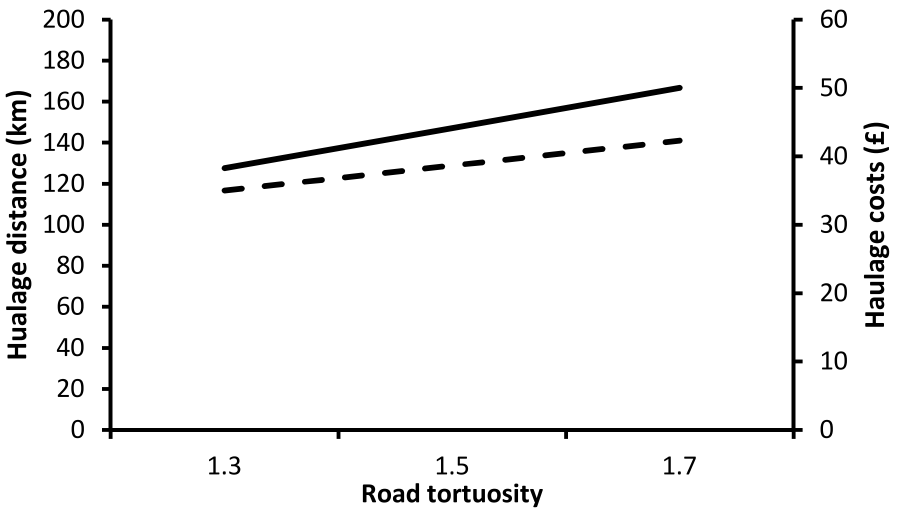


Figure 4.6: Transport distances and haulage costs for the mass of straw required to produce 1,000 L bioethanol (feedstock demand of 500,000 t yr^{-1}, 5 t ha^{-1} yield, D1) for three tortuosity factors. Lines: distance (solid line); costs (dashed lined).

4.6 Discussion

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. The percentage saving in costs from increasing digestibility is more than twice the percentage reduction in transport distances. 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 τ 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. The differences between cultivars are relatively minor at all levels of feedstock demand, S and τ but they suggest that the cost savings from using DPCs will be determined by these factors, which will depend on characteristics of the local area and decisions about biorefinery size.

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).

Such reductions in costs from increased straw yield and digestibility are matched by relatively small increases in *S*. This suggests that distance savings can be achieved by reasonably small increases in *S*. It might prove more feasible to increase *S* rather than encouraging the uptake of these DPCs. However, the feasibility of increasing *S* above the 7% modelled in the current study is unclear, especially given the potential overestimation of current straw supplies resulting from aspects such as farmer reluctance to sell straw (see **Chapter 6**).

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 comparison of the three biorefinery sizes shows that the extent of the cost savings from increasing yield and digestibility increased as feedstock demand increases. This is due to the distance-fixed costs remaining stable whilst distance-variable costs increase. However, it must be considered that the optimum location of a biorefinery is in an area of high-density feedstock production and as feedstock demand increases, finding a sufficiently large area of high-density production becomes less feasible. This suggests that the current model (and potentially other optimisation models that assume circular feedstock supply distribution) may fail to correctly account for feedstock haulage costs for larger feedstock demands.

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.

Sensitivity analysis showed tortuosity factors can have a large impact on the transport distances and costs. As data on tortuosity factors in the UK are unavailable, understanding how uncertainty in the tortuosity factor influences the overall results is important. Leboreiro & Hilaly (2011) found that when optimising the plant capacity, the tortuosity factor can have a large influence on outcomes; they suggest that for optimisation of plant capacity, regional values for tortuosity factors are required. This suggests that the road network can have a large influence on the collection costs and, therefore, should be given consideration when selecting the location of the refinery to reduce transport costs.

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.

4.7 Conclusions

The key findings from this chapter are:

- Increasing straw yield and digestibility offers the possibility of reducing the costs of collecting wheat straw for conversion to biofuel. This is, of course, dependent on all the suppliers growing cultivars with these higher yields and/or digestibility.
- Optimisation of the feedstock demand for UK plants is needed alongside better estimates of feedstock availability in the UK.
- Further work is needed to quantify other benefits of growing cultivars with higher straw yields and digestibility, as well as to quantify trade-offs with grain yield and quality, to determine the feasibility of growing these cultivars.

Chapter 5: Straw production life cycle assessment

5.1 Introduction

In this chapter the environmental burdens (EBs; i.e. emissions and resource depletion) are quantified for the production and delivery of straw from the nine hypothetical cultivars used in **Chapters 3** and **4**. This chapter follows the conventions of a typical LCA; the first section is the goal and scope definitions stage, which describes how the LCA was constructed. The next stage is the inventory analysis, where the raw LCA data is presented, and this is followed by the impact assessment, where the final results are presented. This will be followed by an analysis section comparing the different treatments and an interpretation section where the LCA outputs will be discussed in context of the current literature.

5.2 Literature review

The development of biofuel technology is seen as an important contribution to *sustainable development*. There are many interpretations of sustainable development but the most famous definition is, "…development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations General Assembly, 1987). In general it comprises economic, environmental and social/human aspects, and these are all complexly interrelated. However, there are differences in how these are treated; the mainstream view is that each aspect is a separate entity whereas another perspective is that economic aspects are nested in social/human aspects, which in turn are nested in the environmental aspects, giving the environmental aspects overall importance (Giddings et al., 2002).

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. The importance of this reduction is demonstrated by the Fuel Quality Directive 2009/30/EC, which requires that biofuels have a minimum of 35% GHG savings relative to fossil fuels, with the value of savings increasing to 50% in 2017 and 60% in 2018 for biofuel plants beginning operations after 2016 (European Commission, 2009b). 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).

Assessments must be made to quantify the environmental impacts of biofuels. There are a number of methodologies that can be used for environmental assessments (e.g. Ecological Risk Assessment, Environmental Impact Assessment). Life Cycle Assessment (LCA) is often used as it 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). It is explicitly referenced in important legislation regarding the use of biofuels, including the European Commission's RED, the US Energy Independency and Security Act, the German Sustainable Biofuel Obligation draft, the Swiss directive on mineral oil tax redemption for biofuels, and the UK Renewable Transport Fuel Obligation (Menichetti & Otto, 2009), and it has been used extensively to investigate the environmental impacts of many different biofuel options (Borrion et al., 2012a; Wiloso et al., 2012).

5.2.1 Life Cycle Assessment

LCA originated from various methodologies developed for assessment of packaging and waste management (Baumann & Tillman, 2004). In the early 1990s the methodology was refined and guidelines were published. In 1996, a report was published that applied the LCA methodology to agricultural systems (Wegener Sleeswijk et al., 1996). Agricultural systems, being large and complex, and showing considerable variation in how identical products are created in different areas, presented a number of problems for LCA practitioners. Developing an LCA methodology for agriculture required careful consideration of a number of factors. For example, in the standard LCA methodology, soil would be considered as part of the environmental system whereas for agriculture the soil can be considered part of the environmental system or as part of the agricultural production system (Wegener Sleeswijk et al., 1996).

LCA methodology is constantly evolving but standardised methodologies are available. The International Organization for Standardization (ISO) defined a methodology in the ISO 14040 series (ISO, 1997). In general, LCA studies must conform to the guidelines in this methodology if they wish to be published but there is considerable freedom within this methodology to enable it to be used for highly variable systems.

The ISO methodology divides the LCA into four stages: 1) Goal and scope definition; 2) Life cycle inventory; 3) Life cycle impact assessment; and 4) Interpretation.

5.2.1.1 Goal and scope definition

The goal and scope definition (GSD) stage first involves describing the system under study and defining its function. Questions are formulated during this stage and the LCA tries to answer these questions. The methodology is decided on with the four most critical choices being the definition of functional unit, deciding on the system boundaries and allocation procedure, selecting the type of data to be used and deciding on how the impact assessment is to be made (Baumann & Tillman, 2004). This stage includes stating the intended application of the study, the reason for carrying it out and to whom the results are intended to be communicated. These determine the level of detail required for the data. Assumptions and limitations of the study need to be outlined at this stage. Of major importance is the justification for using a specific methodology. As LCAs are inherently complex, LCA practitioners must make many decisions where there is no right or wrong answer and, because of this, transparency and justification are required so that the reason that decisions were made can be understood.

The functional unit is used to express the function of the system in quantifiable terms and allows comparisons between alternate systems to be made (ISO, 1997). All environmental burdens and outputs are related to this functional unit. When an alternate system is compared that has additional functions not accounted for by the functional unit, then this must be noted in the LCA. It is possible to use two or more functional units to assist in communicating the results or to investigate different aspects of the systems being investigated (Hayashi et al., 2005; Ciroth & Srocka, 2008).

Due to the complexity of production systems boundaries are defined to reduce the data requirement. Aspects that will not have an influence on the final results of the LCA study can be excluded from the study such as shared identical processes in comparisons of alternate production systems (Baumann & Tillman, 2004). Boundaries need to be defined in relation to natural systems, geography and time. They are also needed for the contributing technical systems (Tillman et al., 1994); for example, decisions need to made about whether to included capital goods, which are the objects required to produce the or services utilised in the LCA, such as the factories, tools and equipment required to produce the farm machinery.

When the system under study produces multiple products, the environmental impacts need to be partitioned between them (Baumann & Tillman, 2004), a process known as allocation. All of the emissions from the system must be allocated to the products and this can be achieved based on physical relationships, such as by mass or energy in the products, or by other relationships, such as economic value. If possible, allocation should be avoided by system expansion or increasing model detail (Baumann & Tillman, 2004). The ISO 14041 standard recommends that sensitivity analysis is used if there are several plausible allocation procedures.

Data choices include whether to use average data or find site-specific data. The quality of data is also an important consideration; much more time and expense is required for conducting studies when high precision is required.

The types of environmental burdens that are to be considered are defined in this stage. Set impact assessment methodologies are available and these tend to a have a default set of environmental impacts. It is recommended that all relevant impact categories are included.

5.2.1.2 Life cycle inventory

In this stage a flowchart of the process being modelled is constructed based on the aims of the goal and scope definition. Data is then collected for the activities within the system boundaries, with the sources of the data documented. This might require the conversion of units to fit them to the functional unit. The data collection stage is an iterative process and it is sometimes necessary to review decisions taken during the GSD stage and determine new approaches. This could be a result of an absence of particular data, for example. There might be multiple data sources available and this will necessitate choosing the most appropriate for the aims set out in the GSD. The final stage is calculating the environmental loads of the system in relation to the function unit (Baumann & Tillman, 2004).

5.2.1.3 Life cycle impact assessment

This stage of the LCA attempts to quantify the consequences of the environmental burdens determined in the inventory analysis stage, the purpose of which is to put them into context and facilitate communication (Baumann & Tillman, 2004). It involves grouping environmental burdens into categories and weighting these according to their relative impacts. As an example, the steps for determining the climate change impact category are: 1) identify all emission species that have radiative forcing properties (i.e. GHGs; classification); 2) determine the radiative forcing strength for each emission species relative to that of CO_2 (characterisation); and 3) multiply the amount of each emission species and their relative strength compared to CO_2 to determine the equivalent amount of CO_2 that they represent, which is used as proxy for climate change impact.

There are a number of ready-made impact assessment methodologies, which have specific classifications and weightings (e.g. ReCIpE, CML and Eco-indicator). It is possible to aggregate impacts further into three overarching categories: resource use, human health and ecological consequences. These in turn can be aggregated into a single figure. However, this higher level aggregation is highly dependent on the underlying subjective assumptions making them less reliable for making comparisons (McKone et al., 2011).

5.2.1.4 Interpretation

This stage of the LCA involves reviewing the impact assessments to draw conclusions and provide recommendations (Baumann & Tillman, 2004). The results are presented in various ways depending on who they are being communicated to. This stage also involves an evaluation of the robustness of conclusions drawn. This can take the form of sensitivity analyses, uncertainty analyses and data quality assessments.

5.2.2 Wheat straw SGBs

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 are lower than fossil fuels but emissions of other pollutants, such as those causing eutrophication and acidification, tend to be higher for biofuels.

A number of studies have considered the conversion of wheat straw into bioethanol (see Borrion et al., 2012a). Borrion et al. (2012b) and Wang et al. (2013) have considered this in a UK setting. Borrion et al. (2012) considered one production method based on a US study of ethanol from maize stover (Aden et al., 2002), and considered the emissions from the production and use of E15 and E85 (i.e. fuels consisting of petrol and 15% and 85% ethanol, respectively) compared to petrol. Wang et al. (2013) investigated the emissions from the production of E100 (i.e. a fuel consisting of 100% ethanol) using five pretreatment methods based on an updated version of the US study of ethanol from maize stover (Humbird et al., 2011), and the use of this fuel in a car compared to petrol.

Aspects of these studies that are relevant to the current project are discussed below. In particular, there will be a focus on methodology issues in these studies; in biofuel LCAs these methodological issues have been widely documented (Larson, 2006; Cherubini & Strømman, 2011; McKone et al., 2011; Wiloso et al., 2012).

5.2.2.1 Environmental burdens

The environmental impact categories chosen for LCA studies depend on their purpose (Wiloso et al., 2012). GHG emissions are often considered the main category in assessments of SGB environmental impacts and many studies focus singularly on GHG emissions (e.g. Elsayed et al., 2003; Hsu et al., 2010; Karlsson et al., 2014). This is because in terms of policy goals, reducing GHG emissions is seen as most important (Cherubini & Ulgiati, 2010).

Borrion et al. (2012b) found that using fuel blends with bioethanol reduced GHG emissions by 73% and 13% for E85 and E15 blends, respectively, compared to petrol. However, the types of GHG emissions vary, with N_2O emissions being higher than fossil fuels due to the use of nitrogen-based fertiliser. Wang et al. (2013) found GHG emissions for driving a flexi-fuel vehicle 1 km using E100 were 11-45% lower depending on production method, compared to petrol.

Other than climate change, there are a number of impact categories that should be considered when comparing biofuels to fossil fuels. Kim & Dale (2005) quantified non-renewable energy consumption, acidification and eutrophication. Borrion et al. (2012b) also considered depletion of resources such as water and fossil fuel depletion, ozone depletion and ecotoxicity; the use of ethanol had higher burdens for eutrophication, ecotoxicity and water depletion. Wang et al. (2013) found E100 was favourable in a number of impact categories depending on the conversion method used but all conversion processes gave higher acidification and eutrophication

5.2.2.2 Allocation and system boundaries

The wheat production system has two outputs, grain and straw, and these cannot be decoupled by simple system expansion (Giuntoli et al., 2012) meaning that allocation is required. It is generally recommended to allocate all wheat production processes prior to the separation of grain and straw to the grain and the RED allocates zero emissions to wheat straw prior to its baling (European Commission, 2009a). The straw will only be allocated the processes that are directly related to its production (the product-purpose approach, e.g. Cherubini & Ulgiati, 2010; Hsu et al., 2010; Karlsson et al., 2014) as it is considered a by-product.

There is, however, the argument that straw should be considered a co-product, especially if the price is high enough to have an influence on crop decisions. In which case, it could be argued that straw should be allocated some of the environmental burden of overall crop production. This also allows the identification of improvements in efficiency that would not be obvious if all the emissions are allocated to the grain.

In contrast to other studies, Borrion et al. (2012b) also allocated emissions to the straw left on the fields. This demonstrates the difficulty in agricultural LCAs in differentiating between the economic and environmental systems. The straw could be considered part of the economic system as it is providing a service through the processes described previously (e.g. maintaining SOM) but it could be argued that it should be considered part of the environmental system as its return is maintaining the status quo.

Uihlein & Schebek (2009) and Wang et al. (2013) allocated environmental burdens between grain and straw based on prices, with Wang et al. using average market prices over a five-year period. The argument for economic allocation is that demand drives production (Gnansounou et al., 2009). Economic allocation takes the form of the products' prices. An issue with this is that price alone does not drive production and farmers often base decisions on gross margins. However, as the results of **Chapter 3** have demonstrated, the gross margin relative to price is lower for straw than that for grain and, therefore, prices are less indicative of farmers' choices of crop enterprise. Another issue is that prices fluctuate and the price that will be offered for straw for bioenergy production might differ from the prices offered in the current straw markets.

During sensitivity analysis, Wang et al. (2013) combined allocation techniques: the emissions for overall wheat production were allocated between straw and grain based on price, but on top of these environmental burdens the straw was also allocated the entire environmental burden associated with the fertiliser to replace the nutrients being removed in the straw as well as GHG emissions resulting from SOM oxidation. This method is inconsistent as fertilisers that are applied to replace nutrients removed in the grain are allocated between the grain and straw, but those to replace nutrients removed in the straw are solely allocated to the straw.

Other methods include allocating based on mass (e.g. Borrion et al., 2012b) or energy (e.g. Lindorfer et al., 2014). The European Commission directive 2009/28/EC recommends allocation based on energy content. In the case of wheat production, the use of allocation by mass or and energy would give almost identical results as calorific content is almost identical between grain and straw (de Wit & Faaij, 2010). However, it could be argued that allocation by mass is inappropriate for this assessment because although the calorific content may be similar, the energy required to convert it to a usable product is much higher. For example, less grain is required than straw to produce the same amount of bioethanol (Elsayed et al., 2003). Brankatschk & Finkbeiner (2014) advocate allocation based on the Cereal Unit, which is a measure of metabolisable energy content. However, this method is based on the use of agricultural products as livestock feed so may not represent the intended use of the product. Another argument presented by Gnansounou et al. (2009) is that this method of allocation is unrealistic when co-products are not being used for energy processes. However, the use of allocation by mass does provide consistency compared to allocating by price, given that prices fluctuate and differ between regions.

Giuntoli et al. (2012) used sensitivity analysis to examine allocation based on energy and prices. They compared economic allocation based on straw breakeven price (i.e. fertiliser and contractor costs) and market price and found that market prices led to an 18% increase in climate change impacts. Allocation by energy more than doubled climate change impacts relative to economic allocation by straw breakeven price. Allocating all emissions prior to the separation of grain and straw to the grain reduces emissions by about 60%.

Luo et al. (2000) compared allocation by mass/energy to allocation by price for ethanol from corn stover. They found that GHG emissions were lower for allocation by mass/energy than by price. The reason for this was that the wheat production stage had a net reduction in GHG emissions due to the assimilation of atmospheric CO_2 being greater than the GHG emissions during the production; as mass/energy was allocated more of these emissions it became more favourable.

Further allocation or other procedures are required downstream to separate multiple products during the conversion process. Uihlein & Schebek (2009) used substitution to account for the lignin and xylite produced alongside bioethanol; the emission credits for replacing the separate production of these products are allocated to the system. Borrion et al. (2012b) did not include the downstream products within the system boundaries. Downstream allocation is avoided by using it as an energy credit (e.g. having as credit the emissions required to produce that extra electricity). Wang et al. (2013) assumed that excess electricity was supplied to the National Grid and this gives a co-product credit.

5.2.2.3 Straw production systems

Depending on production and allocation methods, GHG emissions related to wheat straw cultivation contributes between 30% and 60% of total emissions (Wang et al., 2013). The straw production system contributed between 4% and 33% of the environmental burden of the production of bioethanol (Borrion et al., 2012b). This suggests that uncertainty in modelling this stage could lead to significant changes in overall results and shows the importance of accurately modelling this stage.

The level of detail used in modelling the straw production system varies. In models that include the complete wheat production system there are two paths; construction the straw production system as part of the study or using a pre-constructed straw production system from an LCA database. Studies using pre-constructed farm systems include Borrion et al. (2012b) who used a generic European farm system from the Ecoinvent 2.2 database, and Uihlein & Schebek (2009), who also used a standard farm system from Ecoinvent. The benefits of this approach are that these farm systems have been constructed with considerable detail and this saves time and expense constructing a farm system representation. The disadvantage is that these models might not be representative of the systems being assessed, such as with Borrion et al. (2012b) whose assumed farm system has grain and straw yields much lower than average UK yields.

Studies that have constructed their own farm systems include Wang et al. (2013) who constructed their agricultural unit based on the most important processes and inputs. The benefit of this is that UK-specific data was used but there was the disadvantage of there being processes missing, leading to less detail being specified. Even this model appears to not match the farm systems that are likely to be producing straw for biofuel production with the likely source of straw, eastern regions of England, differing from the rest of the country. Therefore, using mean UK data would be less accurate than using eastern-specific data in modelling a likely biofuel production system in the UK.

This is particularly true with regards to using average values for straw yields. Borrion et al. (2012b) used 1.1 t ha^{-1}, which is considerably lower than average straw output and appears to result from double accounting for straw left on the field. This is in contrast to Cherubini & Ulgiati (2010), whose straw yield of 6.94 t ha^{-1} for Austria seems unrealistically high and might be the result of not accounting for residues that are left on the field after harvest (i.e. stubble and chaff). Giuntoli et al. (2012) conducted an LCA for straw for bioenergy for several countries; for the UK, straw production was assumed to be 6.31 t ha^{-1} based on the assumption of a 1:0.8 ratio between grain and straw. Though not made clear, it appears that the whole amount of straw is assumed to be used for bioenergy purpose resulting in an unrealistically high straw yield. As with Cherubini & Ulgiati (2010), it appears the chaff and stubble are included in the straw yield.

Wang et al. (2013) used a straw yield of 3.2 t ha^{-1}, which better matches a UK average. However, average agricultural yields are based on all farmer outputs regardless of aspects such as the scale of the farm, whether the farm is industrially-minded or eco-minded, and the quality of the farming. Brehmer & Sander (2009) used the upper boundary of yields to represent best practice, suggesting that these better represent those farms likely to be supplying straw for biofuel production. Arguably a better estimate of the average straw yield of farms supplying straw for biofuel production in the UK is 5 t ha^{-1} based on the average straw yield for farms supplying Ely power station (Newman, 2003).

When straw is baled the straw chopper on the combine harvester does not need to be used. Elsayed et al. (2003) include an emission credit in calculating ethanol production from straw to cover the emission savings from not using the chopper. They also include emission credits for avoiding extra baling and loss of subsequent crop yield from the incorporation of the straw. Whittaker et al. (2014) also included a straw chopping credit but found overall results only had a minor sensitivity to this. These studies appear to be unique in including straw chopping credit.

Fertilisers

Fertilisers are one of the biggest sources of emissions in straw SGB LCAs (Borrion et al., 2012b; Wang et al., 2013) and, therefore, accurately modelling these is vital. However, there is considerable variation in the amounts specified in the farm systems modelled in LCAs. This is because, as discussed in **Chapter 3**, there is considerable variation in the amounts in straw as well as considerable variation in recommendations for which nutrients need to be replaced.

Whereas P and K appear to be used in almost all straw breakeven price calculations some wheat straw SGB LCAs do not include them. Giuntoli et al. (2012) exclude them, considering them to be irrelevant whilst Karlsson et al. (2014) exclude them assuming that they will be replaced by ash from the biorefinery. However, both of these studies include N, which is often excluded from economic considerations. Wang et al. (2013) calculated additional fertiliser as 68 kg N, 123 kg P, 7 kg K ha^{-1}, with these values taken from Punter et al. (2004) though it is unclear how these values have been calculated. Taking into account the 3.2 t ha^{-1} straw yield, this is equal to 38.4 kg P t^{-1} straw (88 kg P_2O_5) and 2.2 kg K t^{-1} straw (2.6 kg K_2O). Levelton Engineering Ltd. (2000) who used values of 18.3 kg N t^{-1} straw, 3.3 kg P t^{-1} straw and 31.7 kg K t^{-1} straw for Ontario, Canada (based on OMAFRA, 1999, as cited by Levelton Engineering Ltd., 2000) and 6 kg N t^{-1} straw, 1.85 kg P t^{-1} straw and 15 kg K t^{-1} for Western Canada (based on Alberta Agriculture, 1999, as cited by Levelton Engineering Ltd., 2000). Cherubini & Ulgiati (2010) used additional fertilisers of 21 kg N, 10 kg P and 9 kg K per tonne straw (based on 6.94 tons ha^{-1} of straw being harvested). As with estimates of straw value, the uncertainty in the amounts of fertiliser required can mean the fertiliser inputs can widely differ between LCA studies, meaning that it is unclear how accurate the results can be considered to be.

Transport stage

The transport of straw differs in models. Wang et al. (2013) assume a distance of 100 km whilst it appears that Borrion et al. (2012b) did not include this step. Lindorfer et al. (2014) assumed a transport distance of 50 km in Germany but found that the transport of feedstock had minimal influence on overall GHG emissions (except for when all emissions related to grain production were allocated to the grain).

Giuntoli et al. (2012) assumed a distance of 70 km. Transport contributed between 5% and 9% of overall emissions in straw-burning power production. They compared the benefits of straw densification and distance and found only when straw needs to be transport 750 km by road does densification lead to reduced emissions relative to transporting bales.

Uihlein & Schebek (2009) assume a distance of 100 km and found transport contributed to 13-34% impact categories excluding climate change, whose contribution was less than 1%, to the straw production stage. Considering that the straw production stage only contributed minimally to overall emissions it can be considered that the transport stage impacts are negligible.

Indirect impacts

There are two types of LCA: attributional LCA (A-LCA) does not consider indirect impacts from changes in output whereas consequential LCA (C-LCA) does (Brander et al., 2009). C-LCA takes account of processes occurring outside the system boundaries. For example, if the supply of biomass for bioenergy production displaces a current use of that biomass, the changes in environmental burden resulting from that change must be considered. Most studies take the A-LCA approach and assume that the use of the straw does not influence other systems outside the boundaries of the model. Hsu et al. (2010) consider wheat straw not to have a market whilst Giuntoli et al. (2012)

assumed that the straw being used for bioenergy represented the straw that was spare, therefore, not impacting on other straw users.

As discussed in **Chapter 4**, straw will likely be supplied from close to a biorefinery, which means that farmers currently using the local straw might have to import their straw from further away. Ideally, the additional environmental burden resulting from this additional transport should be taken account of; however, accurately determining this additional distance is very difficult, partly because it will very much depend on the local area.

5.2.2.4 Field emissions

As well as emissions from the agricultural processes and production of inputs such as fertiliser, emissions also result from processes occurring in the soil. This includes the conversion of nutrients to other forms that are then moved from the agricultural system, such as through leaching. Nitrogen species make up a large proportion of emissions with NH_3, N_2O and NO_3 being predominant (Brentrup et al., 2000). Agricultural N_2O emissions mainly result from microbial nitrification and denitrification of N fertilisers and crop residues (Velthof et al., 2002). Other direct emissions include phosphorous emissions, heavy metals, pesticides and CO_2 (Nemecek & Kägi, 2007). CH_4 is another direct emission; however, soils can act as a sink for CH_4 (Boeckx & Van Cleemput, 2001).

There is considerable uncertainty and variability in these emissions (Larson, 2006) resulting from them being site-specific with a number of factors influencing their magnitude, including availability of newly fixed N (i.e.

fertilisers), oxidation status, water content, pH, labile organic C and N stocks, vegetation cover, presence of plant litter and earthworms, soil texture, soil compaction, soil disturbance, topography, climate (Reijnders & Huijbregts, 2011).

As these emissions are highly variable and expensive to measure for specific sites, default emissions factors have been made available based on average values (Brentrup et al., 2000). For example, it is sometimes assumed that 1.25% of N in fertiliser and residues left on the field will be converted to N_2O (Nemecek & Kägi, 2007). However, there are issues with using average values and finding appropriate average emissions factors can be difficult (Menichetti & Otto 2009) and, therefore, this must be considered when analysing LCA results. Boeckx & Van Cleemput (2001) considered country-specific N_2O emissions and found that there was a large variation between European countries. Taking account of soil and climate (pedoclimatic) conditions makes for better N_2O emission estimates (Dufossé et al., 2013). Gabrielle et al. (2014) used ecosystem modelling to more accurately estimate N_2O emissions for biofuel production based on pedoclimatic data finding 55-70% reductions in N_2O emissions relative to using default factors.

Studies can differ in which field emissions they include. Most studies include N_2O (Cherubini & Strømman, 2011) but if the studies do not account for impacts other than climate change then emissions such as nitrates and phosphates are excluded. In reviewing FGB LCAs, Smeets et al. (2009) found that N_2O share of overall GHG emissions ranged from 10 to 80%. In SGB LCAs N_2O is an important emission (Cherubini & Strømman, 2011). However, as N fertiliser is the biggest source of these emissions the N_2O will depend on whether N fertiliser is associated with the production of the feedstock; in the case of crop residues, N fertiliser is sometimes not included.

Effect of crop residues on emissions

Of importance to crop residue biofuels is the influence of leaving crop residues on the field as these can affect N_2O emission from soil by: 1) supplying easily mineralisable N; 2) supplying easily mineralizable C, which can enhance denitrifier activity; and 3) increasing the dentrification of residue and soil N; and decrease soil O_2, creating anaerobic conditions that better favour the production of N_2O (Venthof et al., 2002). Laboratory assessments of saturated soil showed straw incorporation increased N_2O emissions (Cai et al., 2001) whilst field experiments found short-term increases in N_2O with wheat straw incorporation (Baggs et al., 2000). Residue C:N ratio influenced N_2O emissions; about 1.9% of wheat straw N was converted to N_2O (Lin et al., 2013). However, Velthof et al. (2002) found N_2O emissions did not increase with wheat straw incorporation.

Other emissions are influenced by straw residues. Gabrielle & Gagnaire (2008) modelled soil impacts from residue removal and found that it led to a slight decrease in N_2O emissions and nitrate leaching, but variable patterns with NH_3 emissions depending on site. Nitrate losses vary with the amount and status of SOM and straw incorporation can lower nitrate leaching (Garnier et al., 2003).

These studies have conflicting findings but in general conclude that leaving feedstock on the field leads to increased emissions, suggesting the removal of crop residues from the field offer a GHG credit as N_2O emissions are being reduced. Kim & Dale (2005) found biofuel cropping systems that utilised greater amounts of residue more favourable due to lower N_2O emissions. Based on Gabrielle & Gagnaire (2008), Cherubini & Ulgiati (2010) used a value of 3 kg N odt^{-1} straw to estimate N_2O emissions resulting from residue left on the field.

5.2.2.5 Soil impacts

Although there are potential benefits of reduced emissions with the removal of crop residue, as discussed in earlier chapters, its removal can cause disadvantages. One aspect that is often overlooked in LCA studies is impacts on the cropping system, in particular the soil, from the removal of crop residue (Larson, 2006, Cherubini & Ulgiati, 2010). This is partly a result of the LCA methodology making it difficult to separate the soil as part of the economic system rather than the environmental system and it is partly due to the difficulties of incorporating a parameter that shows so much variability. However, the effects of crop residue removal on soil should be taken account of in crop residue bioenergy assessments (Cherubini & Ulgiati, 2010). Another reason is that the RED (European Commission, 2009a) is ambiguous on the inclusion of soil carbon changes due to the removal of crop residues. Due to the ambiguity it is often assumed that soil carbon stock changes can be excluded from assessment of crop residue SGBs (Koponen et al., 2013). However, whether to include this potential change can have large impacts on overall GHG emissions (Koponen et al., 2013; Karlsson et al., 2014).

Taking account of soil impacts is difficult in LCA. SOM can be used as a proxy indicator for overall soil health (Milà i Canals et al., 2007), but it is unclear how representative this is for the other benefits that residue incorporation can provide. As discussed in **Chapter 2**, removal of straw has other impacts that go beyond carbon storage and nutrient requirements. Mattsson et al. (2000) defines some benefits of crop residues on the soil including soil erosion, hydrology (e.g. changes to the flow of water as ground water, stream water, runoff, transpiration), SOM (e.g. helps to keep plant nutrients available, contributes to good soil structure, prevents erosion and keeps soil moist), soil structure (i.e. the amount of pore space), soil pH, accumulation of heavy metals.

Gabrielle & Gagnaire (2008) used a model of C and N dynamics in soil-crop systems to investigate the impact of crop residue removal on SOM over a 30-year period and used the data in an LCA of wheat straw for use in a combined heat and power (CHP) unit. Although crop residue removal did reduce SOM they found no significant long-term impacts (Gabrielle & Gagnaire, 2008). The benefits from using the straw to produce biofuels outweighed the increased emissions and reductions in yields. Cherubini & Ulgiati (2010) use data from Gabrielle & Gagnaire (2008) to estimate annual soil carbon loss as 0.27 t ha^{-1}. However, it is unclear how reliable this figure is and where it is applicable. Wang et al. (2013) uses this value from Cherubini & Ulgiati (2010) but it appears that the authors have assumed that is the value for soil loss over 20 years and dividing it by 20 to give an annual carbon loss of 13.75 kg ha^{-1} and, therefore, underestimating GHG emissions. Borrion et al. (2012b) did not consider soil impacts. Whittaker et al. (2014) considered different levels of soil carbon loss with the removal of straw and found variable impacts depending on the assumptions about soil carbon loss; they show the potential GHG emissions could exceed those of the fossil fuel reference system when including soil carbon loss.

Removal of straw can also affect soil C stores though long-term studies differ in their findings. Buysse et al. (2013) found removal of straw reduced soil organic carbon (SOC) whereas Lafond et al. (2009) found no reduction in SOC with straw removal. Lindofer et al. (2014) considered soil impacts from straw removal at the regional level and suggested that the amount of straw that could be sustainably harvested was much lower than existing estimates.

5.3 Goal and scope definition

5.3.1 The purpose of the LCA

The purpose of this LCA is to determine the EBs of producing wheat straw for biofuel production from cultivars differing in their straw yields and digestibilities. Results have been calculated using a partial (cradle-to-gate) LCA starting with the production of wheat and finishing with delivery at the biorefinery gate. 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 results of this study will contribute to our understanding of the feedstock supply chain and, therefore, contribute to the design and implementation of an effective and sustainable supply chain. They will provide an indication of the influence of straw yield and digestibility on the environmental burden of biofuel production.

Aims:

- Design a straw production system that represents the farms likely to be producing straw for UK biofuel production.
- Calculate environmental burdens for the production of straw using an attributional life cycle assessment.
- Determine influence on environmental burdens from increasing straw yield and digestibility.
- Determine the importance of the following on environmental burdens:
    - collection distance;
    - fertiliser to replace the nutrients removed in straw;
    - allocation method;
    - dry matter losses during storage;
    - And equipment performance efficiency and straw yield.

5.3.2 Product definition

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 cultivars being investigated are those outlined in **Chapter 3**.

5.3.3 Functional units

The functional unit will be the amount of straw required to produce 1 litre of bioethanol. The amount for the three digestibilities is presented in **section 3.4.1.1**. This functional unit allows a comparison of the different cultivars.

5.3.4 System boundaries

The boundary between nature and the system is set at the raw material acquisition point. The soil is considered part of the environmental system. It is assumed that the land is currently used for agriculture and, therefore, the production of wheat does not lead to an expansion of farmland. It is also assumed that it does not lead to *indirect land use change*.

The LCA refers specifically to a farm system in the eastern England region (FADN code 412) as this is where a biorefinery is most likely to be located (Glithero et al., 2013a). However, because of limitations with the data, data from other regions and average data is also used. This is explained in more detail in the next section.

The straw production system is assumed to be a current system. However, the study incorporates data from a number of different years as data available on the Ecoinvent 3.0 database was collected at different times. The model only takes account of a single crop season; the fertilisers applied account for the nutrients taken off during the season so it is assumed that the soil is in the same condition as at the start of the prior season.

The production of farm machinery is considered for the majority of processes. The construction and maintenance of buildings are considered.

5.3.5 Data and data quality requirements

The LCA has been constructed using the LCA package SimaPro (version 8.0.2). The agricultural processes data was taken from the Ecoinvent database (version 3.0). Because of the limitations of the processes available some processes were selected that do not correspond exactly with processes in the system under study. The processes were constructed for various central European countries. Field emissions are based partly on the *wheat integrated production* system modelled in the Ecoinvent database. Where available, data corresponding to farming in the eastern region of the UK is used; when this is not available alternative data is used in the following order of decreasing preference: England, UK, Europe, and global.

The model does not take account of variability in the input parameters; rather it attempts to provide an average value.

5.3.6 Reference system

To enable a comparison of the results of the current study, the data output is compared to that of Borrion et al. (2012b). The environmental burdens of the main stages of producing ethanol from wheat straw are provided in **Table 5.1**. This will give an indication of the benefits of the different cultivars in the overall production of ethanol. The feedstock handing stage covers the production of the straw and the supply to the biorefinery. It contributes between 3.7% (water depletion) to 33.4% (marine eutrophication) of total emissions for ethanol production.

Table 5.1: Ethanol production data from Borrion et al. (2012b). H = Feedstock handling; P = Pre-hydrolysis; S = Saccharification and fermentation; E = Ethanol recovery; W = Waste water treatment.

Impact category	Unit	Process				
		H	P	S	E	W
Climate change	g CO_2-eq	963.9	1532.5	841.7	596.0	269.6
Ozone depletion	mg CFC-11-eq	0.04	0.07	0.04	0.02	0.002
Photochemical oxidant formation	g NMVOC	3.52	5.44	3.00	2.06	1.06
Terrestrial acidification	g SO2-eq	40.90	44.91	25.23	15.57	1.05
Freshwater eutrophication	g P-eq	0.30	0.38	0.22	0.13	0.005
Marine eutrophication	g N-eq	44.86	46.79	26.28	16.10	0.39
Terrestrial ecotoxicity	g 1,4-DB-eq	0.79	0.84	0.48	0.29	0.002
Freshwater ecotoxicity	g 1,4-DB-eq	7.73	9.42	5.42	3.29	0.08
Marine ecotoxicity	g 1,4-DB-eq	1.94	3.50	2.10	1.27	0.08
Water depletion	L	1.02	13.60	7.87	4.75	0.23
Fossil depletion	g oil-eq	95.5	295.0	160.3	125.3	101.6

5.3.7 Allocation

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. The straw is considered after it has exited the combine harvester. The fertiliser to replace the nutrients taken off in the straw are allocated completely to the straw. This is considered the baseline scenario.

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*. Values are taken from **Chapter 3**: 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: 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 *gross margins* (see **Table 3.8**).

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*.

5.3.8 Scenario analysis

As well as the allocation scenarios outlined above, a number of scenarios will be considered to determine how other factors might influence the overall results (i.e. the relative difference in the environmental burden of the nine cultivars.) These are based on scenario A1.

- **Equipment performance**: This scenario considers how straw yield influences combine harvester and baler performance. The additional combining required above that for an average yield of straw is allocated completely to the straw. It is assumed that fuel use efficiency increases with higher straw yields.

- **Soil carbon and N_2O credit**: This scenario considers the loss of SOM resulting from the removal of straw and the subsequent CO_2 emissions. It also includes the change in N species emission reductions resulting from removal of residue from the field.

- **Storage losses**: This scenario accounts for potential dry matter loss whilst bales are being stored prior to transport to the biorefinery.

- **Transport distances**: This scenario utilises the transport distances provided in **Chapter 4** to consider how these might influence overall emissions.

5.3.9 Impact categories and methodology

The impact assessment will use the ReCIpE methodology (hierarchist midpoint using the Europe weighting and normalisation; version 1.06, Goedkoop et al., 2009). The impact categories considered are the same as those in Borrion et al. (2012b) to enable comparison with the reference system provided in that study (see **Table 5.1**). The mid-point was used but not the end-point for impact assessments. This is because the end-point methodologies are dependent on assumptions meaning that there is a level of subjectivity in their outputs.

5.4 Inventory

5.4.1 Product flow chart

Due to two main allocation methods being utilised, two flow charts are provided (**Fig. 5.1a, b**). The first model represents the A1 allocation method whilst the second model represents the A2a-c allocation method.

a

b

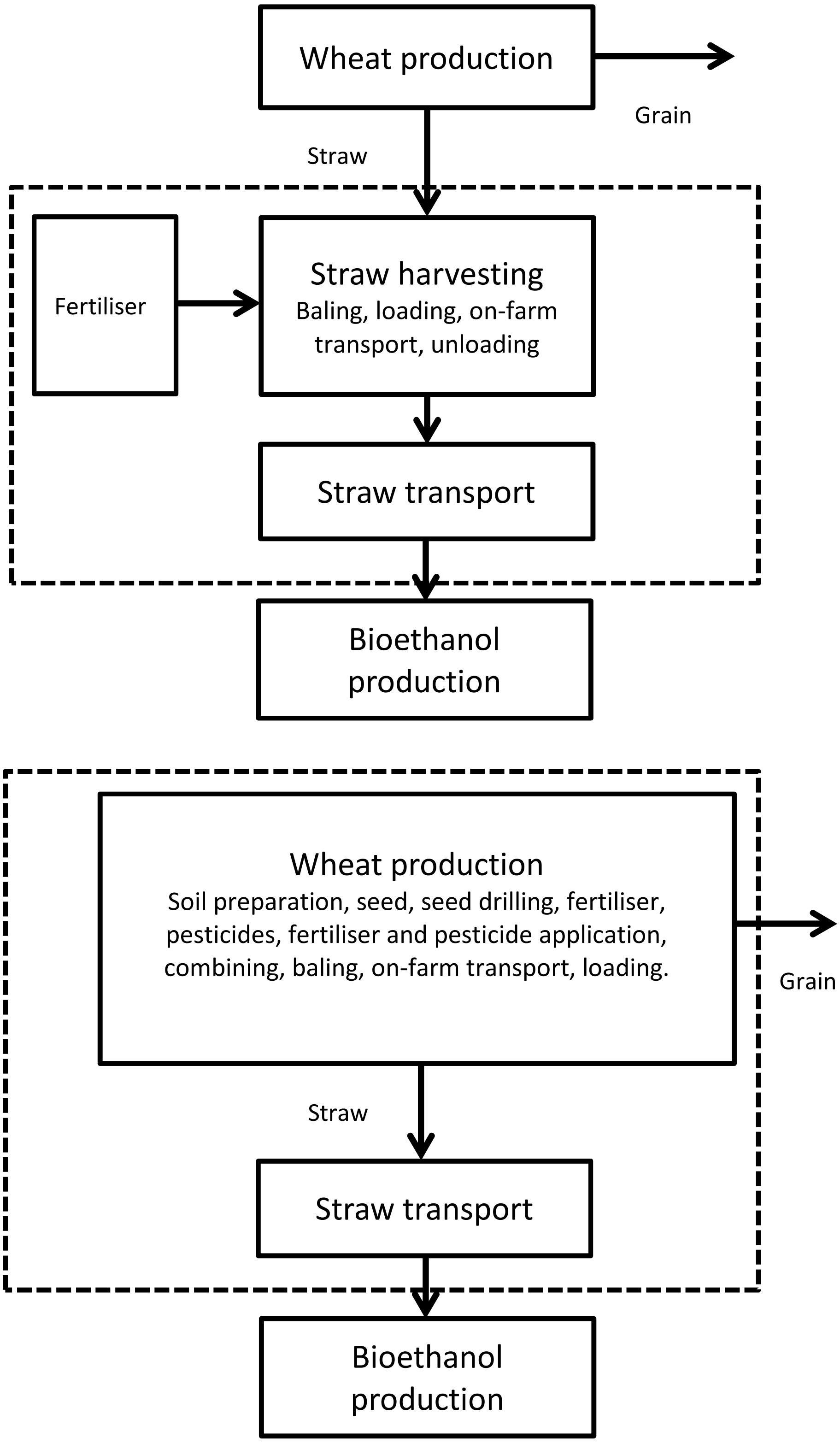


Figure 5.1a, b: Product flow chart demonstrating allocation system A1 (**a**) and allocation system A2a-c (**b**). Dashed lined represents the system boundaries.

5.4.2 Straw harvesting for A1

This covers the baling, loading, unloading and on-farm transport of the straw to the farm gate as well as the fertilisers to replace nutrients removed in the straw. The final product is 1 kg of baled straw at the farm gate.

Replacement nutrients are based in RB209 (2010), which gives the fertiliser required for P_2O_5 as 1.2 kg t^{-1} straw and for K_2O as 9.5 kg t^{-1} straw (as fresh weight). RB209 recommendations do not provide figures for N removed in straw. In this model N is a value of 3 kg t^{-1} straw based on Cherubini & Ulgiati (2010). The types of fertilisers are described in **section 5.4.3.3**. Field emissions from the use of these fertilisers are allocated directly to the straw (see **section 5.4.3.5** for field emission calculations). It is assumed that these fertilisers are applied at the same time as the fertiliser allocated to the grain is applied so the EBs associated with the process of applying this fertiliser to the field are excluded.

The baling is based on the ‘Baling CH/S’ process, which is for a round silage bale of 700 kg of silage and wrapped in PE-film. A correction factor of 0.23 is used to account for the shorter time requirements for baling and no PE-film required (based on Nemecek & Kägi, 2007). The loading of bales is based on the ‘Loading bales CH/S’ process from the Ecoinvent database. The Ecoinvent database does not provide data for the unloading of bales but it is assumed to be the same as loading. A tractor and trailer is used to transport the straw to an intermediate storage location, assuming a distance of 1 km each way.

5.4.3 Straw production for A2

For the A2a-c allocation scenarios a subsystem has been created for 1 ha of wheat cultivation.

5.4.3.1 Field processes

The types of farm processes and the number of operations used for the production of grain are based on Glithero et al. (2012). These comprise ploughing, harrowing, sowing, application of pesticides and fertiliser, and combine harvesting. The on-farm transport of grain is included, assuming a distance of 1 km from the field to the farm storage site. These processes are the same for all cultivars. The baling along with the loading, unloading and on-farm transport of bales vary with the overall straw yield.

5.4.3.2 Seed

The 'Wheat Seed IP, at regional storehouse/CH S' product was used for the emissions associated with seed production and treatment. Treated seed was used because in the UK 95.4 % of seed is treated with pesticides (Garthwaite et al. 2011). Seed rate was 180 kg ha^{-1} assuming thousand grain weight is the same for all cultivars. A transport distance of 15 km from the regional storehouse to the farm by a 'transport, van <3.5 t' was used based on Nemecek & Kägi (2007).

5.4.3.3 Fertiliser

The average fertiliser requirements of N, P_2O_5 and K_2O for a winter wheat are taken from Glithero et al. (2012), which are based on Defra's RB209 fertiliser recommendations (RB209, 2010). The requirements are given as: N = 190 kg ha^{-1}, P_2O_5 = 60 kg ha^{-1}, K_2O = 74 kg ha^{-1}. This is in addition to the nutrients required to replace those removed in the straw, which will vary with the straw yield being modelled. It is assumed organic fertilisers such as farm yard manure are not used. Other nutrients are excluded as they are considered highly variable, only being added when there is a soil deficiency and their contribution to the overall emissions is small (Nemecek & Kägi, 2007).

The types of fertiliser were determined using Defra's survey of fertiliser practice (Anon 2013d). Based on these, the N is split between ammonium nitrate, urea and urea ammonium nitrate in a ratio given in **Table 5.2**. Most fertiliser, in particular P and K fertiliser, is sold as compounds so it is not clear the form of the individual fertilisers. It was assumed that P_2O_5 was in the form of super triple superphosphate and K_2O was in the form of potassium chloride (**Table 5.2**).

Table 5.2: Fertilisers used in the LCA, with their percentage use of the overall nutrient, and the amount of nutrient in the fertiliser

Fertiliser	Use (%)	Nutrient (%)
Urea, as N	15.5	46
Urea ammonium nitrate, as N	13.5	32
Ammonium nitrate, as N	71.0	35
Potassium chloride, as K_2O	100	60
Triple superphosphate, as P_2O_5	100	48

The majority of fertiliser used in the UK is produced overseas (FAOSTAT, 2013) and imported by ship. The fertilisers manufactured in the UK are produced near the ports, where they can be blended to produce fertiliser compounds. These fertilisers are shipped between ports and distributed to farms using road and rail networks. A 2000 report stated that all fertiliser was transport by road (Isherwood, 2000) but the distribution network has changed since that point and now the rail network is also used. Due to the variable production origins and estimating average distances and transportation methods is difficult (pers. comm. Jo Gilbertson, Agricultural Industries Confederation, UK). Without access to more country-specific data, the transportation distances will be used from Nemecek & Kägi (2007), with the only change being to replace transport by barge with transport by transoceanic freight ship (**Table 5.3**).

Table 5.3: Transport modes and distances for fertiliser.

Transport method	N	P_2O_5	K_2O
Rail (km)	100	100	100
Road (km)	100	100	100
Oceanic (km)	900	400	100

5.4.3.4 Pesticides

Data for pesticide application was based on Garthwaite et al.'s (2011) pesticide usage survey with the per hectare application of pesticide calculated by dividing the total active ingredient used by the land area using it. As there are a number of different pesticides used in the UK, generic products from the Ecoinvent database were used for each category. The amounts calculated per hectare are: herbicides (1.317 kg), fungicides (1.332 kg), insecticides (0.088 kg) and PGRs (1.251 kg). The leaching of pesticides to the environment is not included in the LCA and it is assumed that these are minor and, therefore, will only have a negligible impact on the results. It is assumed that these are transported a distance of 15 km by 'transport, van <3.5 t' with the assumption that the active ingredient made up 50% of the total weight (based on Nemecek & Kägi 2007).

5.4.3.5 Field emissions from cultivation

Field emissions vary for the allocation scenarios. In the first scenario (A1), the direct and indirect emissions are calculated solely for the additional fertiliser required to replace that removed in the straw, apart from the soil processes scenario analysis. In the second allocation scenario (A2a-c), all emissions are included and divided between the straw and grain based on the particular allocation method.

Emissions of ammonia (NH_3) to the air

Emissions of ammonia are based on a set of conversion factors for mineral fertilisers (Asman, 1992, as cited by Nemecek & Kägi, 2007). The emissions range from 2-15 % of N converted to ammonia.

Nitrate (NO_3^-) leaching to ground water

Nitrate leaching data is taken from the IPCC guidelines (De Klein et al., 2006), which is the method used in the RED calculations. This method assumes that 30% of all nitrogen in mineral fertilisers and crop residues left on the field is converted to NO_3^-. It is assumed there is 3 kg N t^{-1} straw (Cherubini & Ulgiati, 2009, based on the range of values given in Gabrielle & Gagnaire, 2008).

Crop residues remaining on the field provide a source of NO_3^- (as well as N_2O); when calculating these for allocation scenario A1 the emissions from crop residues that are not baled are allocated to the grain as there would occur regardless of whether straw is baled. However, for allocation scenarios A2a-c, it is assumed that there are 2 t ha^{-1} of crop residue remaining on the field after straw harvest and the emissions from this are allocated between the grain and straw.

Emissions of phosphorous (P) to the water

Leaching of soluble phosphate to ground water (*phosphate, to ground water*) and erosion of soil particles containing phosphorus (*phosphorus, to river*) are taken directly from Nemecek & Kägi (2007). These do not vary with quantity of P fertiliser applied. Run-off of soluble phosphate to surface water (*phosphate, to river*), which does vary with P fertiliser quantity is calculated based on **Eq. 5.1** taken from Nemecek & Kägi (2007):

$$P_{ro} = P_{rol} \times \left(1 + (0.0025 \times P_2O_5)\right) \qquad \textbf{Eq. 5.1}$$

P_{ro} = quantity of P lost through run-off to rivers (kg ha^{-1} yr^{-1}); P_{rol} = average quantity of P lost through run-off for open arable land (0.175 kg P ha^{-1} yr^{-1}); P_2O_5 = amount of mineral fertiliser applied

In the A1 scenario the '1' in the correction factor is discarded as this would be allocated to the wheat production.

Emissions of nitrous oxide (N_2O) to the air

The calculation (**Eq. 5.2**) includes both direct and indirect emissions of N_2O from the conversion of NH_3 and NO_3^-.

$$N_2O = 1.57 \times \left(0.0125 \times (N_{av} - 0.82 \times NH_3 + N_{cr})\right) + 0.01 \times (0.82 \times NH_3) + 0.025 \times (0.23 \times NO_3^{-}) \qquad \textbf{Eq. 5.2}$$

N_2O = Emission of N_2O (kg N_2O ha^{-1}); N_{av} = Available nitrogen in mineral fertilisers (kg N ha^{-1}); N_{cr} = Nitrogen contained in crop residues (kg N ha^{-1}); NO_3^- = Emission of NO_3^- (kg N_2O ha^{-1}); NH_3 = Emission of NH_3 (kg N_2O ha^{-1})

As with the nitrates, it is assumed that there is 2 t ha^{-1} of crop residue remaining on the field after straw collection.

Emission of mono-nitrogen oxides (NO_x) to the air

NO_x emissions are calculated as 21% of the N_2O emissions, though produced in a parallel process so the quantity of N_2O does not need to be corrected (Nemecek & Kägi, 2007).

Emissions of CO_2

During the production of urea CO_2 is bound with the urea. This CO_2 is released whilst the urea is broken down on the field. Emissions are given as 1.570 kg CO_2 kg^{-1} urea-N (Nemecek & Kägi, 2007). CO_2 is also emitted due to the oxidation of soil organic matter and this is considered in the scenario analysis (**section 5.4.5.2**).

CO_2 is taken in by the plant during photosynthesis and would be released during the production and use of the bioethanol. It is recommended that the uptake and release of CO_2 is accounted for in LCAs (Rabl et al., 2007). However, because the conversion step is excluded in the current study, and to make the results clearer, this step is not included in the main assessment.

Emissions of heavy metals

These values are taken directly from Nemecek & Kägi (2007), which are calculated based the agricultural inputs and the leaching of heavy metals from the soil. Unlike the values used in Ecoinvent wheat *Integrated Production* system, the heavy metal emissions are allocated between the grain and the straw in the same allocation ratio as all the other inputs for each scenario.

5.4.4 Transport subsystem

Transport will be based on the energy required to send a truck to the farm to pick up the straw and the return journey to the refinery. The process used is 'Transport, lorry >32t, EURO4/RER'. Loading bales on to the truck is included and is the same as the loading of bales on to a trailer on the field. The unloading at the biorefinery is not included. For all scenarios except the transport scenario, an overall distance of 100 km is assumed (based on Uihlein & Schebek, 2009; Whittaker et al., 2014), giving a tkm (i.e. the weight in tonnes divided by the distance in km) value of 0.1 for each kg of straw.

5.4.5 Scenario analysis

For the A1 allocation method several scenarios are considered:

5.4.5.1 Equipment performance scenario

The combine harvester process is allocated to the straw based on straw yield. The process given is for 1 ha of wheat; assuming that this is for a yield of 8 t ha^{-1} grain and 4 t ha^{-1} straw, with the process allocated completely to the grain. When the straw yield is increased, the work that the combine harvester must do increases (Hill et al., 1987) and this extra work is allocated to the straw. The additional combine harvesting is required for higher straw yields, which, based on having an extra one or two tonnes of material passing through the machine gives a value of 0.083 ha, and 0.167 ha, for 5 t ha^{-1} and 6 t ha^{-1} straw yields, respectively.

It is assumed that baler fuel-use efficiency increases with increased straw yield, resulting in a 5% reduction in fuel use per bale as straw yield is increased from 4 t ha^{-1} to 5 t ha^{-1}, with a further 5% reduction in fuel use as straw yield is increased from 5 t ha^{-1} to 6 t ha^{-1}. Other emissions remain constant.

5.4.5.2 Soil CO_2 and N scenario

Carbon loss from the soil is modelled as 1 t CO_2 ha^{-1} (based on Cherubini & Ulgiati, 2010) and these emissions are allocated to the straw with the value divided by the straw yield of that hectare. This gives 0.25 g kg^{-1} straw, 0.2 g kg^{-1} straw and 0.167 g kg^{-1} straw for overall yields of 4 t ha^{-1}, 5 t $ha^{-1}$and 6 t ha^{-1}, respectively. The carbon savings are, therefore, less per unit of straw as straw yield increases.

It is assumed that an extra 2 t ha^{-1} of straw is left on the field when straw is not baled (see **section 5.4.3.1**). This is assuming that cultivars with lower straw yields would be grown when the straw was not going to be harvested. This leads to an extra N_2O emission of 0.116 kg, nitrate of 7.971 kg and NO_x of 0.024 kg ha^{-1}. Removing straw avoids these emissions. These emissions savings are divided between the straw yields for that field, as with the CO_2 emissions.

5.4.5.3 Transport scenario

All other factors stay the same. Transport distances are those calculated in **Chapter 4** using the same truck as stated previously.

5.4.5.4 Storage losses

The storage losses take place between stacking during the baling stage and the transport stage. It is assumed that 5% of dry material is lost based on Argo et al. (2013). Therefore, for 1 kg straw (at 16% MC) after storage, 1.053 kg straw (at 16% MC) is required prior to storing.

5.5 Results (impact assessment)

5.5.1 A1 allocation

5.5.1.1 Baseline model

The results for the A1 model are given in **Table 5.4**. 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}. 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. 5.2**). The transportation of straw contributed 17%.

Table. 5.4: Environmental burdens for the A1 allocation scenario, for the three digestibilities.

Impact category	Unit	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

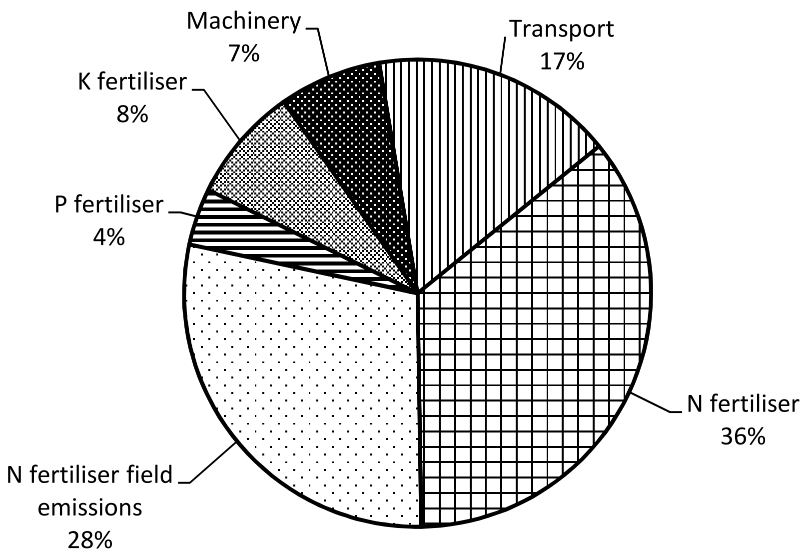


Figure 5.2: Contribution of each component to overall GHG emissions for straw production and delivery. N fertiliser (crosshatch); N fertiliser field emissions (spots); P fertiliser (horizontal bars); K fertiliser (light shading); machinery (dark shading); transport (vertical lines).

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.

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.

5.5.1.2 Storage loss scenario

Including a 5% storage loss before the transport step led to an increase in EBs of between 2.55% and 5.29% for the EB categories. The variation results from the relative contribution of the transportation stage, with larger variation between the storage scenarios being because the amount contributed by the transport stage was lower. As before, there was no difference with straw yield. Differences between digestibility levels were the same as with the baseline scenario.

5.5.1.3 Transport distances scenario

Using transport distances based on the values given in **Chapter 4** instead of a default value leads to minor changes in overall emissions. GHG emissions decrease approximately 2% and 1.5% as yield level increases from 4 to 5 t ha^{-1}, and 5 to 6 t ha^{-1}, respectively. GHG emissions decrease approximately 2.5% and 2.6% as digestibility level increases from D1 to D2, and D2 to D3, respectively. The emissions for other impact categories vary depending on the relative contribution of the transport stage.

GHG emissions increased by approximately 6-8% for increasing feedstock demand from 250,000 t yr^{-1} to 500,000 t yr^{-1}, and 12-14% for increasing feedstock demand from 250,000 t yr^{-1} to 750,000 t yr^{-1}. The other emissions varied in how much they increased; terrestrial ecotoxicity increased by 28.6% when demand was increased from 250,000 t yr^{-1} to 750,000 t yr^{-1}. However, when substituted into the bioethanol production reference model the difference in transport distances only had a minor influence on the bioethanol production overall emissions. This is due to the low contribution of the straw production stage to the overall emissions. These emission savings from increasing straw yield and digestibility increase with feedstock demand.

5.5.1.4 Soil processes scenario

Taking account of soil processes leads to much higher GHG emissions relative to the baseline scenario (**Fig. 5.3**). There are minor reductions in photochemical oxidant formation and terrestrial acidification and a 48.7% reduction in marine eutrophication, due to the decrease in N emissions resulting from less straw left on the field. The percentage differences in emissions between digestibility levels are the same as the baseline scenario.

There is a 20.8% increase in GHG emissions relative to the reference system for straw yield of 4 t ha^{-1} but only a 1.6% increase for the straw yield of 5 t ha^{-1}. For the 6 t ha^{-1} cultivar there is an 11.2% decrease in emissions relative to the reference system. The reason for such a large range is that the CO_2 emissions from the soil are fixed per hectare so increasing the straw yield leads to an allocation of the CO_2 amongst a greater amount of straw.

For the 4 t ha^{-1} cultivar this increases the overall GHG emissions for producing a litre of bioethanol to 3.47 kg CO_2-eq. When assuming that 1.61 kg CO_2 is taken in per kg straw dry matter (Nemecek & Kägi, 2007) this means that the GHG emissions released producing bioethanol is 71% of the CO_2 assimilated. This is before the emissions from its combustion are considered.

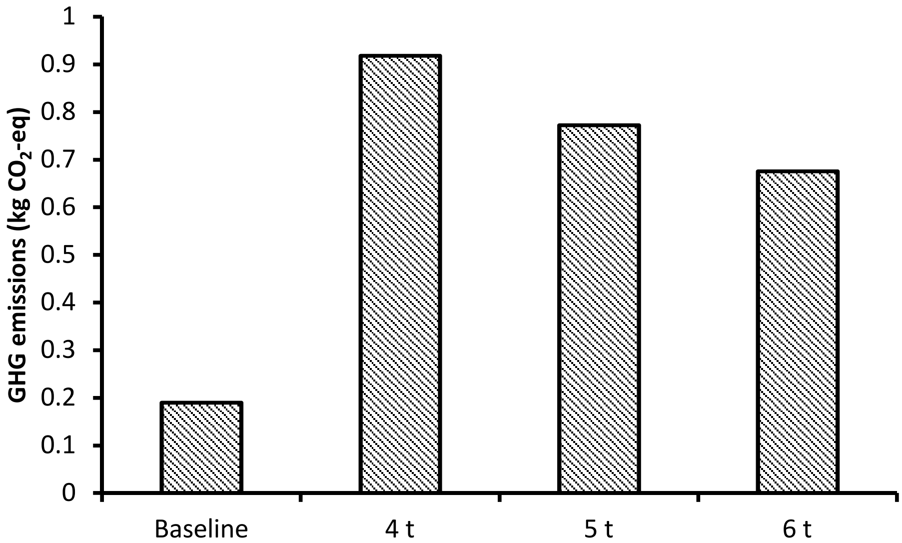


Figure 5.3: GHG emissions for the production and delivery of the amount of straw required to produce a litre bioethanol for the baseline scenario and the three yield levels (at D1) for soil processes scenario.

5.5.1.5 Equipment efficiency scenario

Taking account of equipment performance led to increases in emissions for the higher straw yields. However, these higher emissions were small so only led to negligible differences to overall emissions when substituted into the reference system. The percentage differences in emissions between digestibility levels are the same as the baseline scenario. Increasing yield from 4 t ha^{-1} to 5 t ha^{-1} increases emissions from between 0.13% to 17.73% with further increases for an increase to 6 t ha^{-1}. Increasing the baling efficiency whilst omitting the combine harvester process leads to negligible decreases in emissions for the higher straw yields.

5.5.2 Allocation scenario A2a

For all EBs except water use, values were lower for A2a 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.

5.5.3 Allocation scenario A2b

When compared to price allocation (A2a) use of gross margins for allocation reduced EBs in the range of 34.1% to 41.7%. 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 would see 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.

5.5.4 Allocation scenario A2c

Allocation by mass 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.

5.5.5 Allocation scenarios compared

Allocation made a large difference to the EBs. GHG emissions were highest for the allocation by mass scenario (A2c) whilst for the other allocation scenarios they were lower relative to the reference system (**Fig. 5.4**). 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; **Fig. 5.5**). 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 (**Fig. 5.6**). All allocation scenarios had higher water depletion than the reference system.

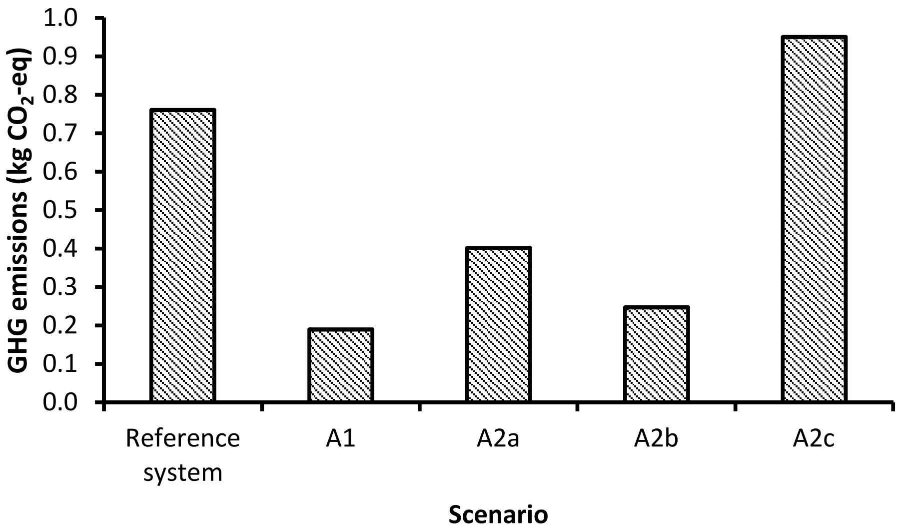


Figure 5.4: GHG emissions for the straw production stage for producing straw for 1 L of bioethanol for the four allocation scenarios and reference system. Straw yield = 4 t ha^{-1}; Digestibility = D1.

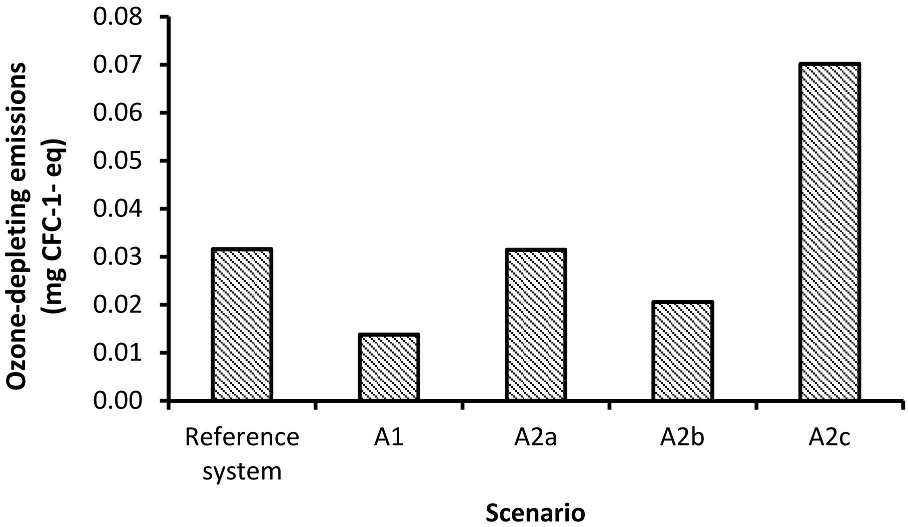


Figure 5.5: Ozone-depleting emissions for the straw production stage for producing straw for 1 L of bioethanol for the four allocation scenarios and reference system. Straw yield = 4 t ha^{-1}; Digestibility = D1.

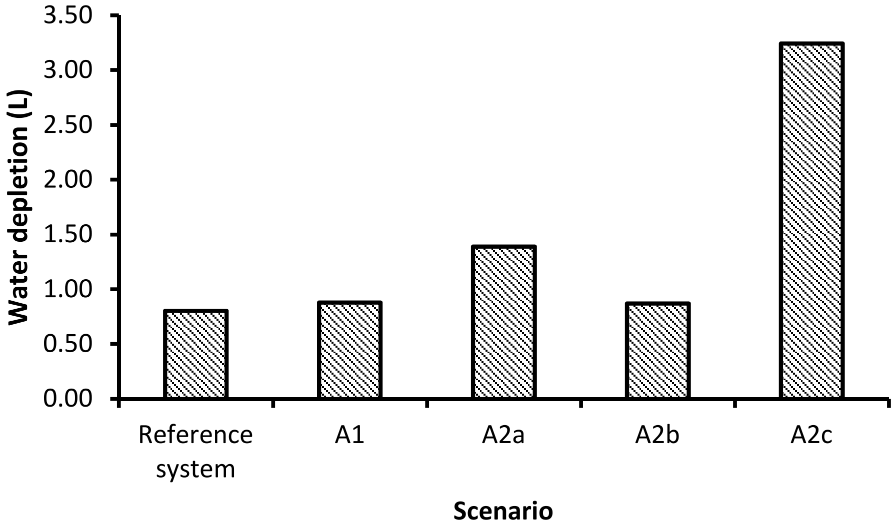


Figure 5.6: Water depletion for the straw production stage for producing straw for 1 L of bioethanol for the four allocation scenarios and reference system. Straw yield = 4 t ha^{-1}; Digestibility = D1.

5.6 Discussion

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. (2000) 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. (2000) 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 work in **Chapter 3** 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.

For all allocation scenarios, water depletion was higher than the reference system, further supporting that there is a trade-off of having higher water depletion. However, the impact of water depletion is difficult to quantify. The ReCiPe impact assessment methodology (Goedkoop et al., 2009) does not include an end-point indicator as the impacts of water use will vary greatly with location and water source. In the UK, the location of water extraction will greatly determine its impact with some regions having considerably more water than others. Impact assessments have attempted to more thoroughly quantify impacts from water use; an example is the method developed by Pfister et al. (2009) that takes into account aspects such as the quality of the water and regionalised factors using watershed delineation and relates it to damage to human health, ecosystem quality and resources.

The current LCA and that of Borrion et al. (2012b) are designed to be general models and not represent specific locations. This is why the mid-point indicators are used rather than end-point indicators. They demonstrate that the production and use of bioethanol from wheat straw can be beneficial compared to petrol use but what is important is that the biorefinery is located in a place that minimises the impact of the environmental burdens; for example, in places where water availability is not limited and ecosystems are not particularly susceptible to damage from the specific emissions.

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 RED allocation rules and, 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).

As discussed in **Chapter 3** there is considerable variability in the amounts of these nutrients removed from the field in the straw leading to uncertainty in knowing the amounts of fertilisers that need to be applied. The current LCA did not include fertilisers other than N, P and K but the removal of straw will lead to a greater demand for Mg, S and Ca. However, the amounts required are small and because of this they are not considered to have a large enough effect to include in the Ecoinvent database (Nemecek & Kägi, 2007).

Reducing fertilisers, such as S and Mg, would only have a small contribution to overall emissions and their reduction might be more beneficial in terms of economics than environmental. However, there are some possibilities in reducing them. One suggestion is using the ash produced during biofuel production as a fertiliser, thus reducing the amount of fertiliser that needs to be mined and produced (Skøtt, 2011). This ash could be transported from the biorefinery to the field in the trucks collecting the straw.

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 **Chapter 4** it is likely feedstock sourcing distances will be limited by costs rather than considerations regarding transport emissions.

The current model used an A-LCA approach; if a C-LCA approach is taken then additional straw transport might need to be taken account of due to displaced local straw supply for other straw users. This could further increase the emissions associated with the production of biofuels by, for example, requiring straw users to source their straw from further away leading to higher emissions. This does not appear to have been considered in current LCAs of the production of biofuels from wheat straw. However, as discussed previously Mendlesham straw-burning power plant failed to gain planning permission because of fears of competition with other straw users. This suggests that any biofuel biorefinery will only be built if impacts on other straw users were limited.

In the soil processes scenario, emissions and emission credits were the same per hectare, which meant the amount allocated to each unit of straw was determined by the per hectare straw yield. This provides a benefit to higher straw yields in terms of spreading the emissions from the oxidation of SOM between greater amounts of straw. Inclusion of these led to large increases in GHG emissions, with oxidation of SOM far outweighing the reduction of N_2O emissions from removing straw residue. This would suggest that the benefits of the return of straw outweigh those of its removal. Whereas the baseline scenario was much lower than the reference system, GHG emissions for the production of bioethanol were higher for the soil processes scenario than in the reference system. This highlights how variable results can be dependent on whether these aspects are taken into account. Whittaker et al. (2014) found that the loss of SOC was matched by the reduction in N_2O emissions from not leaving the straw on the field.

However, these soil processes are highly variable and the current study only captured a single value for each. Work is required to better estimate these emissions for the areas in England that are likely to supply straw for biofuel production. This could follow Dufossé et al. (2013) by using pedoclimatic modelling. Some research suggests that SOM will reach equilibrium after a certain period of time (e.g. Powlson et al., 2011); therefore, the influence on straw removal on the amount of SOM depends on the time-scale being considered. The longer the time-scale considered, the lower the emissions allocated to each year.

There is limited information on how equipment efficiency is influenced by straw yield. This work provides an example of how increasing straw yield might lead to variation in emissions. It also suggests that treating the straw as a by-product might lead to incorrect conclusions about the benefits of increasing straw yield; this is because the combine harvester process is often allocated to the grain stage and the additional combine harvesting resulting from higher straw yields would not be accounted for. This suggests that in determining the effect of increased straw yield combine harvesting should be included. Further work is needed to determine, in particular, the machinery impacts from growing higher straw yields.

Although not considered in this experimental work, downstream allocation could be an issue for determining the benefits of increased digestibility. The by-product of the production of bioethanol is likely to be energy in the form of electricity and/or heat produced from the lignin left over from the processing step (Aden et al., 2002). In this work it is assumed that less straw is required from cultivars with higher digestibility material to produce the same amount of bioethanol; however, this will likely to lead to less lignin being available and, therefore, less energy as a by-product. This lessens the benefits of high digestibility material but is likely to negligible.

5.7 Conclusions

The main findings of this chapter are:

- Allocation method had a large influence on the extent of environmental burdens.

- Environmental burdens for most impact categories were lower in the A1 allocation scenario than the reference system, further strengthening the favourability of bioethanol over petrol.
- Accounting for the loss of SOM can cause much higher GHG emissions.
- The influence of increased straw yields and digestibility on environmental burdens depended on the allocation scenario. Increasing digestibility tended to only lead to a small reduction in environmental burdens. Increasing straw yield did not alter environmental burdens under the A1 allocation scenario but when soil processes were included there were large differences in GHG emissions between straw yields.

Chapter 6: Current and future straw production and use

6.1 Introduction

This chapter addresses how the development of a new market for wheat straw as feedstock for bioenergy might influence farmer decision making. The main objective of this chapter is to put the previously presented results into context by considering how farmers would react to changes in the price of wheat straw. To achieve this, a farmer survey was conducted to investigate the views of farmers regarding cultivar selection and how they might change their practices given a new market.

6.2 Literature review

6.2.1 Deciding to supply straw

Understanding the behavioural intentions of farmers will be vital in developing a cellulosic biofuel sector. One of the most important aspects requiring investigation is whether farmers are willing to supply feedstock (Thivolle-Cazat et al., 2013). 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. This is even though one of the key drivers for the development of biofuels is economic development of the rural sector (Nuffield Council on Bioethics, 2011).

In many estimates of crop residue available for bioenergy, little thought is given to farmer behaviour. Some studies assume that farmers will supply feedstock at the breakeven production price (e.g. Gallagher et al., 2003; National Research Council, 2011) or for the breakeven price plus a percentage to cover risk, management and profit margin (e.g. 15% in MAFRD, 2014). Others estimate crop residue availability for biofuel production based on current production and use but do not take into account whether farmers would be willing to sell residues that could be sustainably removed (e.g. Malins et al., 2014). Others use arbitrary assumptions for farmer willingness to supply straw, such as Petrolia (2008) who assumes a 50% farm participation in feedstock supply.

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, and in a survey of farmers in Missouri and Illinois, Altman et al. (2013) found that 42% and 39% of farmers, respectively, were not willing to make their hay, wheat straw or corn stover available to sell in a biomass market, though it is unclear if they were already using their residues for other uses. Due to simplified assumptions it is possible that feedstock availability has been overestimated (Tyndall et al., 2011). However, as considerable policy and research investment is based on estimates of energy potential from biomass, accurate information is vital. For example, resource availability, which included feedstock availability, was one of the dominant sources of uncertainty in entrepreneurial decision making with regards to an emerging renewable energy technology (biomass gasification projects in the Netherlands; Meijera et al., 2007).

The simple assumptions about the supply of straw result from both a lack of knowledge about farmer willingness to supply feedstock, and the difficulty in incorporating such data into models due to the many factors that influence decisions to sell straw. The US *Billion-Ton Report* (U.S. Department of Energy, 2011) does not consider willingness to sell in its estimates of feedstock availability because it states that there is insufficient information to be able to do this. A better understanding of farmer decision making in general, in particular to understand non-economic influences on decision making, is of great interest to policy makers in government (Edwards-Jones, 2006); farmer willingness to sell feedstock represents a gap in knowledge and this could significantly influence policy decisions.

6.2.1.1 Considerations for selling straw

There are a wide range of factors influencing decisions regarding crop or enterprise choices and business activities (Edwards-Jones, 2006). The ability to sell straw will depend on whether there is a market offering sufficient prices for straw in close enough proximity. Conditions of the contract are also important; Glithero et al. (2013b) found that farmers had differing opinions about what straw contracts they would prefer but were more interested in supplying a fixed area or, to a lesser extent, an amount dependent on farm surplus. Altman et al. (2013) suggest that both spot and contract-style purchasing methods should be used to encourage sufficient supply. Farmers were also interested in having quality premiums for their crop residues (Fewell et al., 2013).

As discussed in **Chapter 3**, the price offered for straw must take into account many different components. Various breakeven prices have been calculated for crop residues and these have been used to estimate producers' willingness to supply. However, basing calculations of feedstock availability on breakeven prices is inaccurate as farmers are often unwilling to sell straw at these prices. Mooney et al. (2013) found that the majority of farmers in southwestern Wisconsin were unwilling to sell their straw for the breakeven prices given in the literature. In Glithero et al. (2013b) the average price farmers wanted for selling straw was £50 t^{-1}, which is higher than the breakeven price calculated in the literature and this current project (see **Chapter 3**).

Some analyses incorporate a premium above the breakeven price to reward farmers for the time and effort required to organise the collection of straw (Aden et al., 2002), but this still does not provide a perfect estimate of straw supply. Whilst profit-maximisation is often the major goal of farmer behaviour, socioeconomic and psychological variables can also have strong influences on behaviours (see Willock et al., 1999 for references). Attitudes, which are defined by Willock et al. (1999) as 'a positive or negative response towards an attitude object (where an attitude object may be a person, idea, concept or physical object)' are considered to have an important role in determining farmer behaviour (Edwards-Jones, 2006). Due to decisions often being based on more than profit-maximisation, understanding the decision process about selling straw is problematic and, therefore, it is difficult to quantify straw availability for bioenergy based on price alone.

There are a number of considerations in addition to price that must be made when deciding whether to supply straw. Aspects such as the impacts on soil discussed in **Chapter 2** are a major consideration for farmers. Glithero et al. (2013b) found that 24% of farmers surveyed incorporated straw for the benefits it provides to the soil. Other impacts on the soil include damage during the collection of straw from compaction by farm machinery, which was another reason why many farmers incorporated straw. The requirement of additional fertiliser to replace that taken by straw removal was also cited (Glithero et al., 2013b). However, it has been suggested that farmers are *over conservative* when deciding how much crop residue to retain, and tend to incorporate more than is needed for nutrient recycling (Kretschmer et al., 2012). Nutrients could be replaced through the return of biological digestate or ash from bioenergy processes (Glithero et al., 2013b). However, basing the rate of straw incorporation on nutrients alone ignores the other benefits that residue retention provides. In particular, SOM levels, the benefits of which were described in **Chapter 2**. However, even when baling, organic material is returned to the soil from the roots and stubble and, therefore, the loss of SOM is often negligible provided that the straw is not removed every year; Powlson et al. (2011) suggest that baling operations should be limited to every other year at most.

Other aspects to consider include timeliness, where the collection of straw delays other farm operations such as the establishment of the following crop. Glithero et al. (2013b) found that 28% of farmers did not supply straw due to timeliness of operations. Farmers wishing to bale straw may either purchase their own equipment or hire agricultural contractors. Purchasing equipment requires financial investment, a greater amount of labour and an increased complexity of farm operations, which needs much greater coordination of farm resources (Glithero et al., 2013b). Conversely, concern about contractors with respect to a perceived lack of control over farm operations is one reason why some farmers are unwilling to sell their straw. Further issues include straw requiring lengthy storage periods and concerns about arson of stored straw.

Farmer decision making is also influenced by attitudes to the environment (Willock et al., 1999), and this might impact on the supply of residue for biofuels. As an example, Jensen et al. (2007) compared farmer willingness to grow switchgrass for bioenergy production to a number of variables, one of which was membership of an environmental organisation; however, this factor did not influence willingness to grow switchgrass. A major aspect determining whether a farmer will sell straw for biofuels is their opinion towards biofuels. Work in this field has focused on decision making with regards to establishing bioenergy crops (Mattison & Norris, 2007).

6.2.1.2 Risks and uncertainty

Risk and uncertainty play a major role in agricultural decision making (Moshchini & Hennessy, 2001). Weather conditions during the baling period provide an example of this; uncertainty about what weather conditions will be present at harvest means that deciding to bale straw carries with it the risk of the problems that are typically encountered when baling in wet conditions. These include difficulties for mechanical straw collection as well as increased the chance of straw spoilage during storage if the straw is baled with high moisture content (Copeland & Turley, 2008); farm traffic is also more damaging to soil under wetter conditions (Håkansson et al., 1988) so the negative impacts on the soil from baling are increased in wet harvest periods.

As discussed previously, uncertainty is also present in the impacts of straw removal on soil quality, in particular in the long-term. Most farmers are considered to be risk adverse and they will often choose options where there is a significant chance of success even if it means a lower expected return (Harwood et al., 1999). In surveying farmers in North Dakota, Maung et al. (2012) found that farmers wanted to avoid taking any risk when supplying crop residues by transferring ownership immediately after harvest, and having an external party undertake the baling and collection operations.

6.2.2 Farm surveys

In the current study a survey was used to assess current and future straw use actions and attitudes. Access to complete lists of British farm addresses is restricted making finding a suitable sampling frame difficult (Mattison & Norris, 2007). Business directories are sometimes used for creating a sample frame (e.g. Morris et al., 2000; Carter, 2001; Mattison & Norris, 2007; Lobley & Butler, 2010); however, this leads to coverage error because these do not contain the entire population. In studies of the coverage of the sample frames of phone directories, several authors have found them to be incomplete. Burton & Wilson (1999) found that life-style farmers and economically constrained farmers appear to be less likely to appear in the Yellow Pages. Harrison (1991, as cited by Burton & Wilson, 1999) suggests that land-owners who are more business-minded are more likely to provide public access to their details than those who value farming as a 'way of life'. There is disagreement about how representative a business directory as a sampling frame is of farm size; Burton & Wilson (1999) suggest that farm size is the same between sampled farms from a phone directory and those sampled from a complete sample frame (i.e. all farms); however, Emerson and MacFarlane (1995) found that farms in the Yellow Pages were likely to be larger. In general, these studies suggest that using a phone directory as a sampling frame can lead to sampling error and coverage error.

Using a business directory as a sampling frame has other limitations. For example, more than one business may be represented by a single entry or *vice versa*; entries might be factually incorrect; and temporal inaccuracies occur when subjects die, change occupation or relocate (e.g. Burton and Wilson, 1999; Emerson and MacFarlane, 1995; Lobley & Butler, 2010).

Nonresponse bias must be considered when conducting a survey. This is where subjects in the sample frame who fail to respond to the survey would differ in their responses to the information being collected in the survey (Dooley & Lindner, 2003). Not accounting for nonresponse bias can skew results and, therefore, restrict the generalisation of the results to the population being sampled. However, nonresponse bias is often neglected from survey studies:

for example, in assessing survey articles in the Journal of Agricultural Education, Lindner et al. (2001) found that the majority of studies did not address nonresponse bias. Dooley & Lindner (2003) found the same with the journal Human Resource Development Quarterly.

There are various methods for testing for nonresponse bias: 1) Comparison of the responses of early and late responders (see Miller & Smith, 1983; Dooley & Lindner, 2003; Tyndall et al., 2011) using a T-test to test for significant differences between the mean responses for key farm/farmer variables, such as number of years farming and area farmed; 2) Comparison of characteristics of the sample to agricultural census data using a T-test; 3) Using 'days to respond' as a regression variable, and regressing primary variables of interest on the variable 'days to respond' (Lindner et al., 2001); 4) Comparison of respondents' characteristics to nonrespondents by sampling a minimum of twenty nonrespondents (Lindner et al., 2001). The results of these tests indicate whether the survey results can be used to make general inferences about the entire population.

6.3 Aims

The aims of the survey are to:

- Identify cultivar selection criteria and the sources of information used for selection.
- Identify uses of wheat straw from the 2012 harvest.
- Determine straw supply should the price offered for straw increase.

- Determine management practices that might be used to increase straw yield should straw price increase.
- Compare these findings to farm characteristics and farmer attitudes to determine any correlations.

6.4 Methodology

To achieve these aims, a postal survey was conducted. The survey followed Dillman's tailored design survey protocols (Dillman et al., 2008). Pilot work took place during the development of the survey and this involved discussing the survey with farmers and individuals with prior experience of conducting farmer surveys. The survey was sent with a covering letter describing the survey (**Appendix 5**). A pre-paid addressed envelope was provided for respondents to return the survey. To encourage participation respondents were entered into a prize draw to win gift vouchers for a department store. The survey was sent out in December 2012; this time of year was chosen to maximise response rate as it was expected that it was a less busy period for farming operations.

6.4.1 Identifying survey participants

The survey population was in the eastern side of England as this is where the greatest straw surpluses are found (Copeland & Turley, 2008) and is, therefore, the most likely site for a biorefinery (Glithero et al., 2013a). All counties within the North East, Yorkshire, East of England, East Midlands, and South East were surveyed. The survey frame was based on addresses from Yellow

Pages and the Thomson Directory, which were supplied by the company Experian.

A total of 2,000 questionnaires were sent; 1,245 addresses were collected from the Thomson Directory with the Business Activity class ‘Farming – Crops’ and 755 addresses from the Yellow Pages with the Business Activity class ‘Farmers’. The addresses were limited for these farms with only 36,877 addresses for the UK when the Yellow Pages classification “Farming” was selected against an estimated 105,449 holdings in England in 2010 (Defra, 2011). The sample of 2,000 farmers represents approximately 4% of the farms in these regions (Defra, 2011). Due to the limited information on the contacts, not all farms would be wheat producers, thus limiting the potential responses. The returned surveys did not require contact details meaning it was not possible to identify unreturned surveys and this prevented unreturned responses from being followed up.

Due to the errors associated with using business directory data as a sample frame, nonresponse checking was conducted to determine how representative the survey results are of the entire wheat-producing farming population in these regions.

6.4.2 Survey questions

The survey is presented in **Appendix 6.** An overview of the questions is given below:

- The survey asked questions on the county where the farm was located, the age of the farmer and the size of the farm. It had a Likert-scale rating of the importance placed on farming objectives. The respondent was asked to provide information on the crops grown for harvest in 2012 and the livestock held on the farm that year. They were asked whether they had any other enterprises on farm.
- Questions six and seven asked respondents how frequently they changed cultivars and the average number they grew at a time, respectively. Questions nine and ten used a Likert-scale rating to assess the importance of cultivar characteristics on respondents' cultivar choices and the sources of information used to select cultivars.
- Question eight asked respondents about the uses of the wheat straw from the 2012 harvest.
- Questions 11 to 13 looked at the potential future straw supply: Question 11 asked at what price respondents would start managing their wheat crop to increase straw yield. Question 12 asked respondents whether they would be willing to sell extra straw if the price was to increase to £100 t^{-1} baled. Question 13 asked whether respondents would utilise any particular management practices to increase straw yield should the price reach £100 t^{-1} baled.

6.4.3 Data sorting

The Farm Business Survey methodology was used to determine farm type. The value of each farm enterprise (given as a standard outputs) was estimated using information collected in the survey and the relative values of these enterprises was used to establish a farm type. The data collected in the survey did not have the level of detail for an exact determination of the standard gross margins of the farm so these were approximated based on the available data. The values used are given in **Appendix 7**.

Some assumptions had to be made when analysing data. Question eight asked farmers about their wheat straw from the 2012 harvest but sometimes the responses were incomplete, such as only accounting for a portion of the wheat straw or combining wheat straw with other cereal residues. When a portion of the straw was missing, it was allocated to chopped and incorporated. This was because it was assumed that the farmers would have a much clearer idea of the amount of straw they had baled than they had incorporated, and would have answered with the amount of straw that was baled and not answered with the remainder. When residues from other cereals were included, sometimes it was clear from the amounts allocated to each use which crop was responsible for and it was possible to allocate based on that. However, when that was not possible an average was taken.

For some Likert-scale ratings, averages were calculated by assigning the numbers one to five to *very unimportant* to *very important*. This value is just used for exploring the data and is not used as a statistical analysis.

6.4.4 Statistical analysis

Standard linear regression was used to compare *days to respond* against farm size for nonresponse checking. T-tests were used to compare early to late responders.

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. To reduce type 1 error the Bonferroni correction was used, with P calculated as $0.05/x$, where x = the number of comparisons (based on MacDonald & Gardner, 2000). 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.

6.5 Results

6.5.1 Survey responses

The survey received 686 responses (34.3% of the total sample population). Of these, 133 (6.7%) were from respondents who did not grow wheat, and 24 (1.2%) could not be completed because of various reasons, the main one being retirement. This left 529 responses from farmers that grew wheat (26.5% of the total sample population) although 13 responses were removed due to being incomplete. Of the 516 responses that were used in the analysis, most were missing at least one piece of data (answered a question with N/A) but were included in the analysis as it would have greatly limited the data to exclude these responses.

6.5.2 Response groups

The responses were divided into groups based on farm size and type, farmer age and region and these are presented below.

6.5.2.1 Region

The number of responses per region is given in **Table 6.1**. A small number of responses did not provide a county or region in their responses and these are classified as *unknown*. The mean values for farm size, the area of wheat grown, number of crops, proportion of feed wheat and years of farming experience of the respondent are given for each region in **Table 6.2**. Attitudes did not significantly vary with region (**Table 6.3**). However, for profit maximisation there was a trend for respondents in East Midlands to have a neutral opinion.

Table 6.1: The number of questionnaires sent and responses received for each region, showing the proportion returned and the proportioned used in the analysis.

Region	**Questionnaires**		**Prop. returned**	**No. used**	**Prop. used**
	Sent	**Returned**			
East Midlands	437	148	0.34	112	0.26
East of England	628	211	0.34	180	0.29
North East	123	31	0.25	18	0.15
South East	363	129	0.36	89	0.25
Yorkshire	449	127	0.28	97	0.22
Unknown	-	37	-	20	-
Total	2,000	686	0.34	516	0.26

Table 6.2: Means for farm and wheat areas plus number of crops, proportion of wheat grown that is of feed quality and years of experience for each region.

Region	Farm size (ha)	Wheat area (ha)	No. of crops	Prop. feed wheat	Years of experience
East Midlands	520.50	216.36	4.51	0.82	25.38
East of England	433.35	216.09	4.07	0.64	26.51
North East	423.75	142.83	3.94	0.61	23.00
South East	397.42	151.87	3.97	0.45	27.82
Yorkshire	263.78	115.59	4.54	0.77	25.87
Unknown	750.80	373.90	4.40	0.57	20.13

Table 6.3: Chi-square analysis results of farmer attitudes and region.

Attitude	Chi	P
Land stewardship	9.08	0.336
Maximising yields	12.69	0.123
Maximising gross margins	7.02	0.535
Maintaining the environment	6.56	0.585
Profit maximisation	15.36	0.053
Quality of life	10.49	0.232
Leisure and work balance	3.09	0.928
Family objectives and succession	12.34	0.137
D.f. = 8		

6.5.2.2 Farm size

Farms were divided into Defra farm size categories (<5 ha, 5<20 ha, 20<50 ha, 50<100 ha, >=100 ha); however, from this it appeared that the data was biased to larger farms. For example, there were no farms with fewer than 5 ha and only two with fewer than 20 ha. Approximately 84% of respondents were in the category of 100 ha or above. However, the Defra categories are based on holding size whereas the survey question did not separate between holding size and overall farm size; some responses were for farms that had multiple holdings.

Data returns were then divided into a new set of sizes to separate the farms of area 100 ha and above. However, it must be remembered that these are arbitrary categories and do not represent any particular business structure. The key data for each category is given in **Table 6.4**. Overall, the survey responses cover a total area of 219,900 ha, with 97,958 ha of wheat grown in 2011-12.

Table 6.4: Frequency of respondents per farm size group and means for farm and wheat areas plus number of crops, proportion of wheat grown that is of feed quality and years of experience for each farm size group.

Farm size (ha)	Frequency	Area of wheat (ha)	No. of crops	Proportion feed wheat	Years of experience
<50	23	19.0	2.61	0.61	25.48
50-99	60	35.5	3.23	0.78	27.39
100-149	76	55.4	3.70	0.65	27.45
150-199	52	81.2	4.08	0.65	29.90
200-249	58	98.6	4.02	0.73	25.36
250-299	27	117.3	4.81	0.51	28.69
300-499	91	173.8	4.53	0.56	26.08
500-999	73	291.5	5.12	0.71	24.87
>=1000	56	731.8	5.25	0.74	20.15

The attitude ratings (for neutral, important and very important) were compared between farm size groupings (**Table 6.5**). The only significant difference was for gross margins where for farms under 100 ha, farmers were less likely to rate gross margins as very important. Profit maximisation was close to being significant and followed the same pattern as gross margins. Maximising yields was close to being significant with farms below 200 ha more likely to rate maximising yields as neutral.

Table 6.5: Chi-square analysis results of farmer attitudes and age group.

Attitude	Chi	P
Land stewardship	15.13	0.127
Maximising yields	17.70	0.060
Maximising gross margins	22.98	0.011
Maintaining the environment	12.67	0.243
Profit maximisation	18.02	0.055
Quality of life	8.02	0.627
Leisure and work balance	5.22	0.876
Family objectives and succession	13.36	0.204
D.f. = 16		

6.5.2.3 Farm type

The survey did not ask the type of farm the respondent was from so farm type was determined using Defra groupings based on the standard outputs of the farms. These farm types were divided into general cropping (116 farms), cereals (363 farms) and other (e.g. specialist pigs, specialist poultry, dairy; 37 farms). The key data for the three groups are given in **Table 6.6**.

There were no significant differences in attitudes between farm types (**Fig. 6.7**). There was a trend for maximising gross margins with 'other' farm types being more likely to have a neutral opinion towards gross margins than expected.

Table 6.6: Frequency of farm types and means for farm and wheat areas plus number of crops, proportion of wheat grown that is of feed quality and years of experience for each farm type.

Farm type	Frequency	Size (ha)	Wheat area (ha)	No. of crops	Prop. feed wheat	Years of experience
Cereals	363	406.4	199.4	3.91	0.66	26.45
General Cropping	116	531.8	189.8	5.36	0.65	24.45
Other	37	288.8	91.2	3.97	0.87	26.89

Table 6.7: Chi-square analysis results of farmer attitudes and farm type.

Attitude	Chi	P
Land stewardship	5.73	0.220
Maximising yields	1.46	0.833
Maximising gross margins	8.81	0.066
Maintaining the environment	5.88	0.208
Profit maximisation	0.30	0.990
Quality of life	4.64	0.327
Leisure and work balance	4.34	0.362
Family objectives and succession	5.23	0.264
D.f. = 4		

6.5.2.4 Farmer age

The key information for each age category is given in **Table 6.8**. There were no respondents under the age of 25. Attitudes did not significantly differ between age groups (**Table 6.9**). For some questions, older farmers were less likely to answer them (in particular questions 11 to 13), making differences between age categories difficult to determine.

Table 6.8: Frequency of respondents per age group and means for farm and wheat areas plus number of crops, proportion of wheat grown that is of feed quality and years of experience for each age group.

Age group	Frequency	Size (ha)	Wheat area (ha)	No. of crops	Proportion feed wheat	Years of experience
25-34	12	531.6	226.3	5.17	0.76	5.91
35-44	54	753.3	321.5	4.30	0.61	10.32
45-54	155	442.8	187.1	4.54	0.68	20.38
55-64	171	394.9	164.3	4.18	0.69	28.61
65-74	94	291.0	148.6	3.87	0.64	36.54
>=75	21	334.1	197.6	3.90	0.67	49.45
N/A	9	255.6	116.3	3.56	0.57	25.00

Table 6.9: Chi-square analysis results of farmer attitudes and age group.

Attitude	Chi	P
Land stewardship	9.16	0.517
Maximising yields	15.94	0.101
Maximising gross margins	11.79	0.300
Maintaining the environment	12.88	0.231
Profit maximisation	6.60	0.763
Quality of life	6.62	0.761
Leisure and work balance	9.31	0.503
Family objectives and succession	11.24	0.339
D.f. = 10		

6.5.2.5 Representativeness of 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. Average farm size for cereal and general cropping farms for each region are given in **Table 6.10**. 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. As mentioned earlier, this 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.

Table 6.10: Average farm size on different farm types in different regions. Population data is from 2010 data from Defra's June Survey (Defra, 2011). N.B. General cropping data from the current investigation's survey for South East and North East regions are based on small sample sizes (n = 7 and 2, respectively).

Region	Mean farm size (ha): Population data		Mean farm size (ha): Survey responses	
	Cereal	General cropping	Cereal	General cropping
North East	157.4	71.6	374.3	685.0
Yorkshire	128.9	109.6	271.3	262.8
East Midlands	169.0	116.7	402.0	902.8
East of England	154.7	145.6	449.7	403.3
South East	200.4	58.8	407.3	487.1

Responses were compared to *a priori* data on average farmer age. The most common age group was 55-64 years old (n = 171) closely followed by 45-54 years old (n = 151). The median age group was 55-64 years old. The median age of UK farm holders in 2010 was 59 years old (Anon, 2012b). 14% of UK farm holders were under 45 years old in 2010 (Anon, 2012b) with 13% of respondents in this study. However, this is for the whole of UK and the respondents to the survey were not necessarily the farm holder.

The diversification activities responses were compared to data from Defra statistics (Defra, 2012). Diversification enterprises were found on 41% (n = 211) of the farms compared to 24% of commercial holdings in in England 2010. These findings support the idea that the sampling frame is biased towards more commercially-oriented farmers when using directories as the sample frame.

Nonresponse bias was tested by comparison of early to late responders. The first 50 responses were compared to the last 50 responses and only small differences were found between farm size (374.6 ha for early responders compared to 444.9 ha for late responders; P = 0.394), years as principal manager (23.64 years for early responders compared to 23.60 years for late responders; P = 0.987) and number of crops grown (4.24 crops for early responders compared to 4.54 crops for late responders; P = 0.363). Regression of *days to respond* (for surveys used in the study) to the size of farm found there was not a significant relationship (P = 0.349).

In conclusion, the survey appears to be biased to towards larger, more market-oriented farms. These issues were also seen with surveys by Morris et al. (2000) and Lobley & Butler (2010); however, they suggested that over-representation of larger farms was acceptable as they account for a large proportion of the land and resources. Morris et al. (2000) argue that using business directories as a sample frame allows a greater sampling of commercial farmers, who are of more interest to these types of studies.

6.5.3 Wheat cultivars

6.5.3.1 Mean number of cultivars grown (Question seven)

The mean number of wheat cultivars grown was 2.62 (assuming the 5+ category referred to 5 cultivars) and the most commonly grown number was two (**Fig. 6.1**). The number of cultivars grown did not significantly differ between regions ($\chi_{(15)}$ = 6.87; *P* = 0.961) or farm types ($\chi_{(8)}$ = 12.73; *P* = 0.122). The number of cultivars grown varies with farm size ($\chi_{(20)}$ = 251.61; *P* <0.001), with a greater number of cultivars grown with increasing farm size. The number of cultivars grown significantly differed between age categories ($\chi_{(15)}$ = 24.36; *P* = 0.018); farmers aged under 45 were more likely than expected to grow five or more cultivars, farmers aged 45-54 were more likely than expected to have four cultivars, farmers aged 55-64 were more likely than expected to have two or three cultivars and farmers 65 and over were more likely than expected to have one or two cultivars. This can, in part, be explained by the average farm size being greatest for younger farmers (see **section 6.5.2.4**).

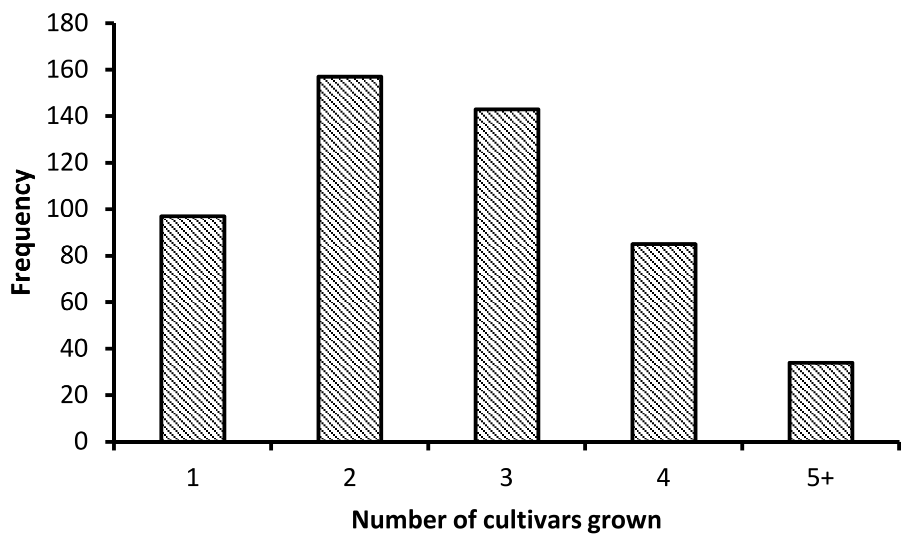


Figure 6.1: Counts of the cultivars grown and responses for all returned questionnaires.

6.5.3.2 Frequency of change (Question six)

Respondents changed cultivars on average every two to three years (**Fig. 6.2**). Frequency of change did not significantly differ between age groups ($\chi_{(15)}$ = 6.87; P = 0.961) and farm type ($\chi_{(6)}$ = 6.68; P = 0.352). However, frequency of change did vary with region ($\chi_{(12)}$ = 24.59; P = 0.017) with the frequency of change tending to be longer for the East of England and the South East and shorter in the other regions, and also with farm size ($\chi_{(15)}$ = 28.78; P = 0.017) with larger farms tending to change cultivars more frequently.

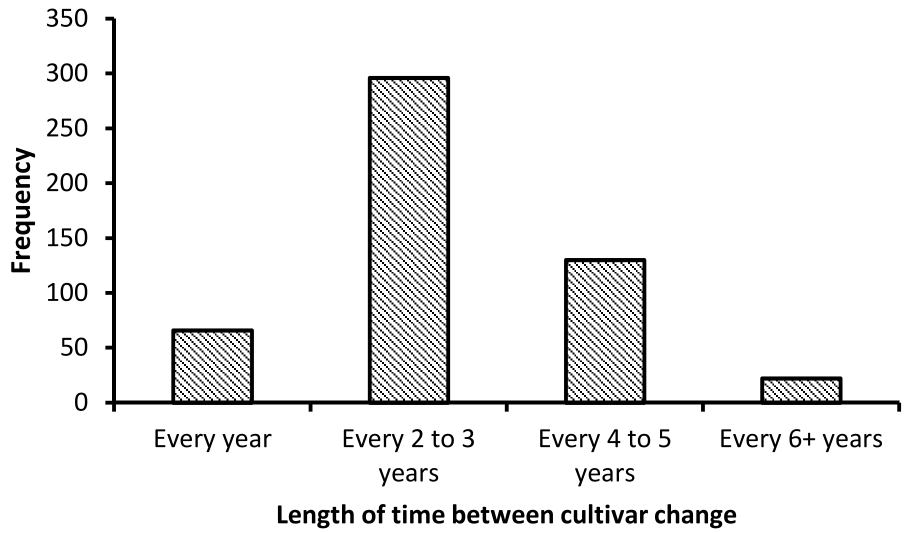


Figure 6.2: Frequency of change of cultivars for all returned questionnaires.

6.5.3.3 Important characteristics (Question nine)

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. 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 (**Table 6.11a**) *customer preferences and contractual requirements* were more likely to be rated as neutral than expected. For farm size (**Table 6.11b**), farms under 100 ha were much more likely to have a neutral opinion of *potential gross margins* than expected. For farmer age (**Table 6.11c**), there was a trend for more farmers than expected over 65 years old to rate *disease resistance* as very important. For region (**Table 6.11d**), 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 saw *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 ($\chi_{(2)}$ = 12.03; P = 0.002).

Table 6.11a: Chi-square analysis results of importance rating for cultivar characteristics and farm types.

Characteristic	Chi	P
Potential gross margins	6.64	0.156
Grain yield	0.77	0.943
Resistance to lodging	3.21	0.523
Seed cost and availability	0.85	0.932
Resistance to disease	7.24	0.124
Crop timing constraints (e.g. sowing/harvest dates)	7.80	0.099
Customer preferences and contractual requirements	19.35	<0.001
D.f. = 4		

Table 6.11b: Chi-square analysis results of importance rating for cultivar characteristics and farm size groups.

Characteristic	Chi	P
Potential gross margins	24.05	0.007
Grain yield	15.90	0.103
Resistance to lodging	8.49	0.581
Seed cost and availability	8.80	0.551
Resistance to disease	12.67	0.242
Crop timing constraints (e.g. sowing/harvest dates)	14.28	0.161
Customer preferences and contractual requirements	12.26	0.268
D.f. = 10		

Table 6.11c: Chi-square analysis results of importance rating for cultivar characteristics and farmer age groups.

Characteristic	Chi	P
Potential gross margins	12.93	0.227
Grain yield	11.49	0.321
Resistance to lodging	5.92	0.822
Seed cost and availability	10.65	0.385
Resistance to disease	17.46	0.065
Crop timing constraints (e.g. sowing/harvest dates)	10.13	0.429
Customer preferences and contractual requirements	3.89	0.952
D.f. = 10		

Table 6.11d: Chi-square analysis results of importance rating for cultivar characteristics and regions.

Characteristic	Chi	P
Potential gross margins	4.98	0.760
Grain yield	16.03	0.042
Resistance to lodging	11.32	0.184
Seed cost and availability	7.94	0.439
Resistance to disease	5.55	0.697
Crop timing constraints (e.g. sowing/harvest dates)	17.54	0.025
Customer preferences and contractual requirements	34.40	<0.001
D.f. = 8		

6.5.3.4 Information for cultivar selection (Question ten)

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 *HGCA RLs* with 88% of respondents noting they were important or very important for their selection of cultivars. However, slightly more respondents gave the *HGCA 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 (**Table 6.12a**) 'other' farms more likely to be neutral to *own knowledge and experience* and *customer preference and contractual requirements*. For farm size (**Table 6.12b**), farms over 300 ha were more likely to cite *HGCA 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 more information sources to base their decisions on. Ratings did not significantly differ between farmer age groups (**Table 6.12c**). For region (**Table 6.12d**) *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 (HGCA, 2013).

Table 6.12a: Chi-square analysis results of importance rating for cultivar information sources and farm types.

Information source	Chi	P
HGCA recommended lists	4.81	0.308
Own knowledge and experience	21.16	<0.001
Agronomist	2.23	0.693
Word-of-mouth (e.g. neighbouring farmers)	5.79	0.215
Customer preference and contractual requirements	12.85	0.012
D.f. = 4		

Table 6.12b: Chi-square analysis results of importance rating for cultivar information sources and farm size groups.

Information source	Chi	P
HGCA recommended lists	73.76	<0.001
Own knowledge and experience	58.38	<0.001
Agronomist	21.78	0.016
Word-of-mouth (e.g. neighbouring farmers)	12.57	0.249
Customer preference and contractual requirements	77.90	<0.001
D.f. = 10		

Table 6.12c: Chi-square analysis results of importance rating for cultivar information sources and farmer age groups.

Information source	Chi	P
HGCA recommended lists	7.58	0.670
Own knowledge and experience	11.03	0.355
Agronomist	12.58	0.248
Word-of-mouth (e.g. neighbouring farmers)	8.57	0.574
Customer preference and contractual requirements	4.98	0.892
D.f. = 10		

Table 6.12d: Chi-square analysis results of importance rating for cultivar information sources and regions.

Information source	Chi	P
HGCA recommended lists	13.41	0.099
Own knowledge and experience	5.59	0.693
Agronomist	7.91	0.442
Word-of-mouth (e.g. neighbouring farmers)	5.16	0.741
Customer preference and contractual requirements	18.46	0.018
D.f. = 8		

6.5.4 Wheat straw use (Question eight)

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 on in the swath (**Table 6.13**). 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 6.13: 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.

6.5.4.1 Region

The use of straw for each region is given in **Table 6.13** and **Fig. 6.3**. The East of England had the highest proportion of straw chopped and incorporated, followed by the East Midlands and the South East. The North East had the lowest proportion.

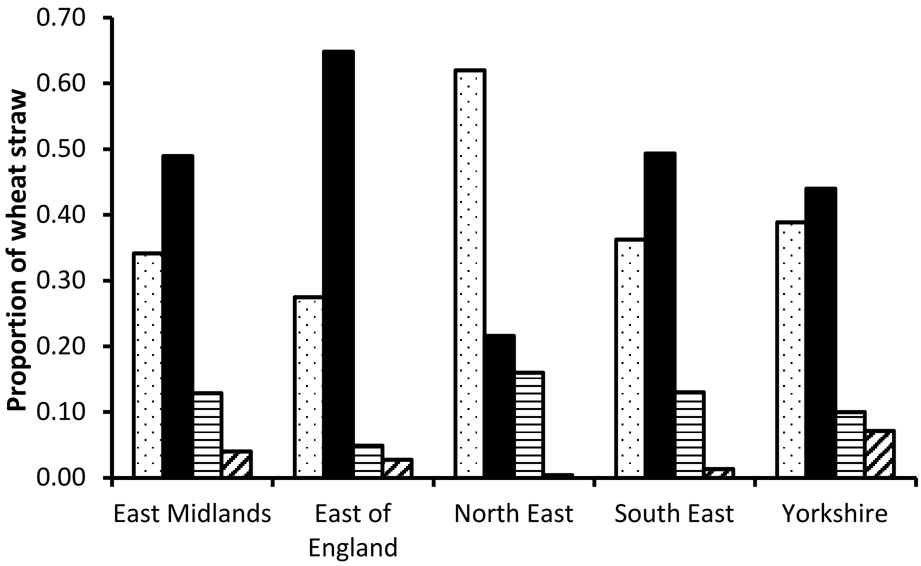


Figure 6.3: Mean percentage uses of straw for each region. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).

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; **Fig.**

6.4). 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 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.

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 is.

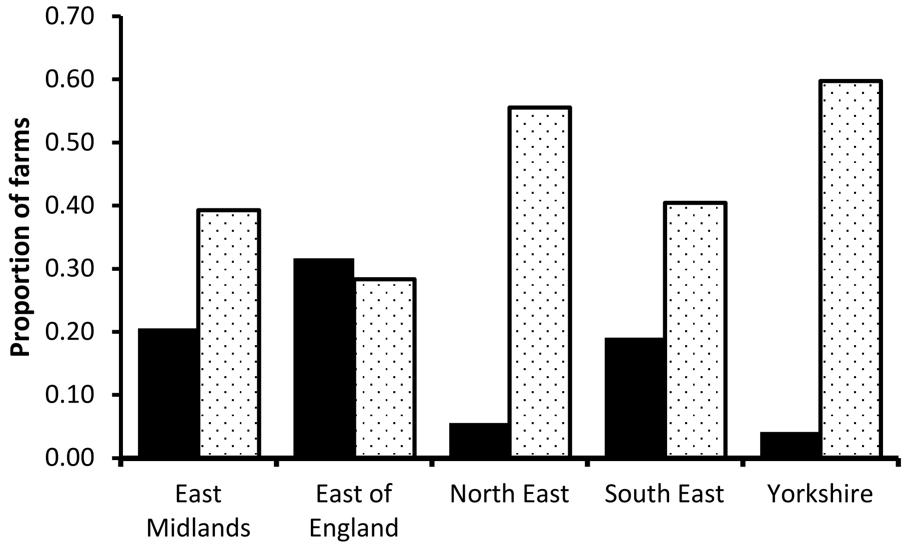


Figure 6.4: The proportion of farms that chopped and incorporated all or no straw in 2012 for different regions. Farms chopping and incorporating all straw (solid bar); farms chopping and incorporating no straw (dotted bar).

6.5.4.2 Farm size

The use of straw for each farm size category is given in **Fig. 6.5**. 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; **Fig. 6.6**). 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; **Fig. 6.6**). 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.

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.

The proportion of each use of straw for different wheat area categories is given in **Fig. 6.7**. This data supports that straw incorporation increases with wheat area.

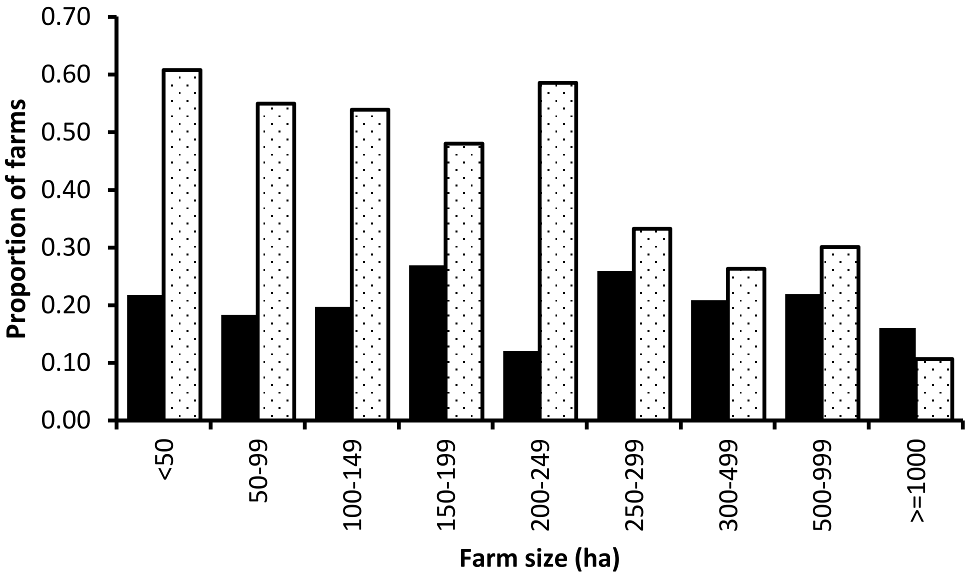


Figure 6.6: The proportion of farms that chopped and incorporated all or no straw in 2012 for different farm size categories. Farms chopping and incorporating all straw (solid bar); farms chopping and incorporating no straw (dotted bar).

The proportion of straw baled for on-farm use and used for other purposes is low and fairly consistent across farm size categories. The proportion of straw used on-farm was fairly consistent across farm sizes. However, when considering the amount of wheat grown, farms growing less than 20 ha of wheat tended to use a considerably greater proportion of straw on the farm than larger wheat areas (**Fig. 6.7**); approximately half of the farms growing less than 20 ha of wheat were livestock farms. The proportion of straw sold is highest for farms less than 250 ha in size. There appears to be a correlation between the amount of wheat grown and the proportion of straw chopped and incorporated.

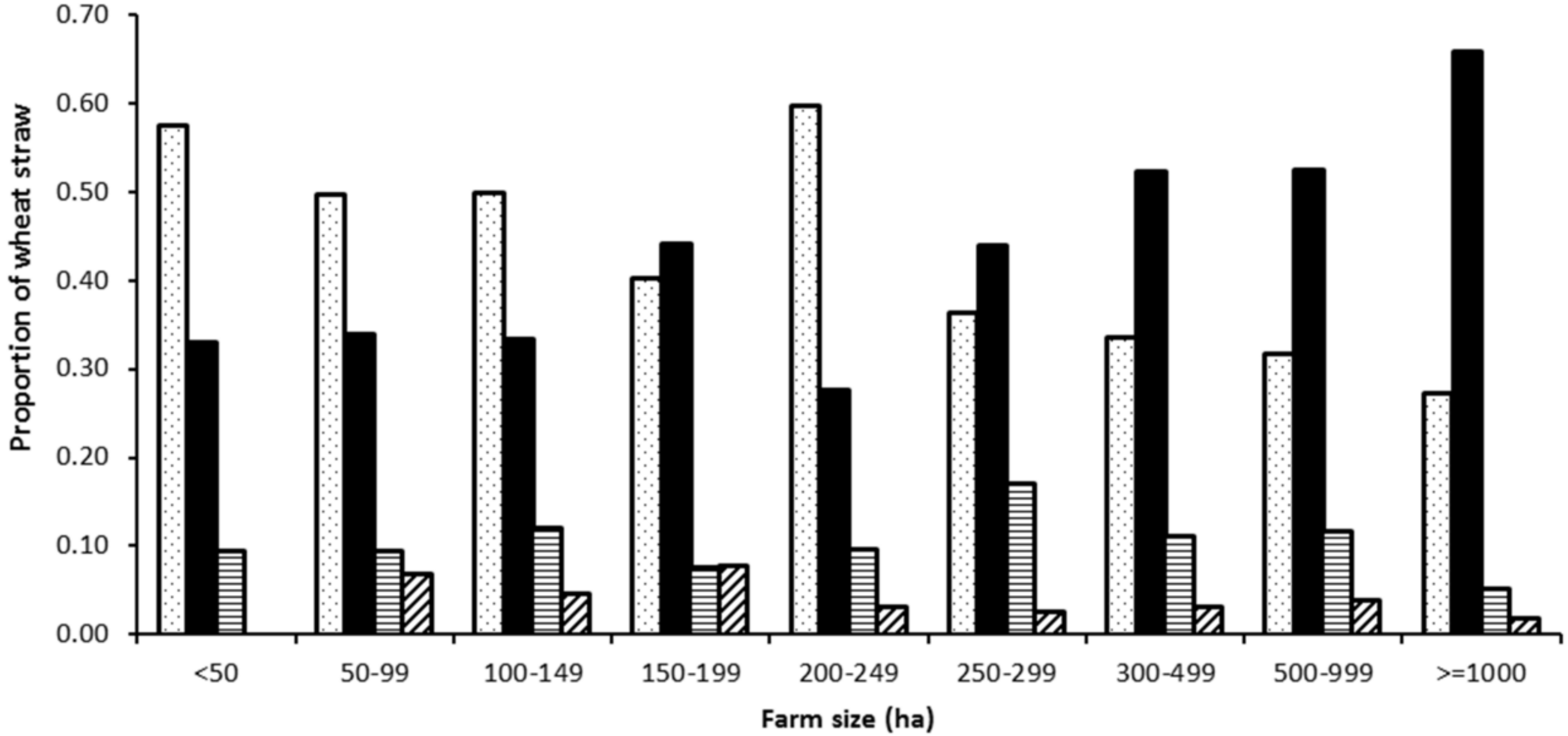


Figure 6.5: Mean percentage uses of straw for farm size groupings. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).

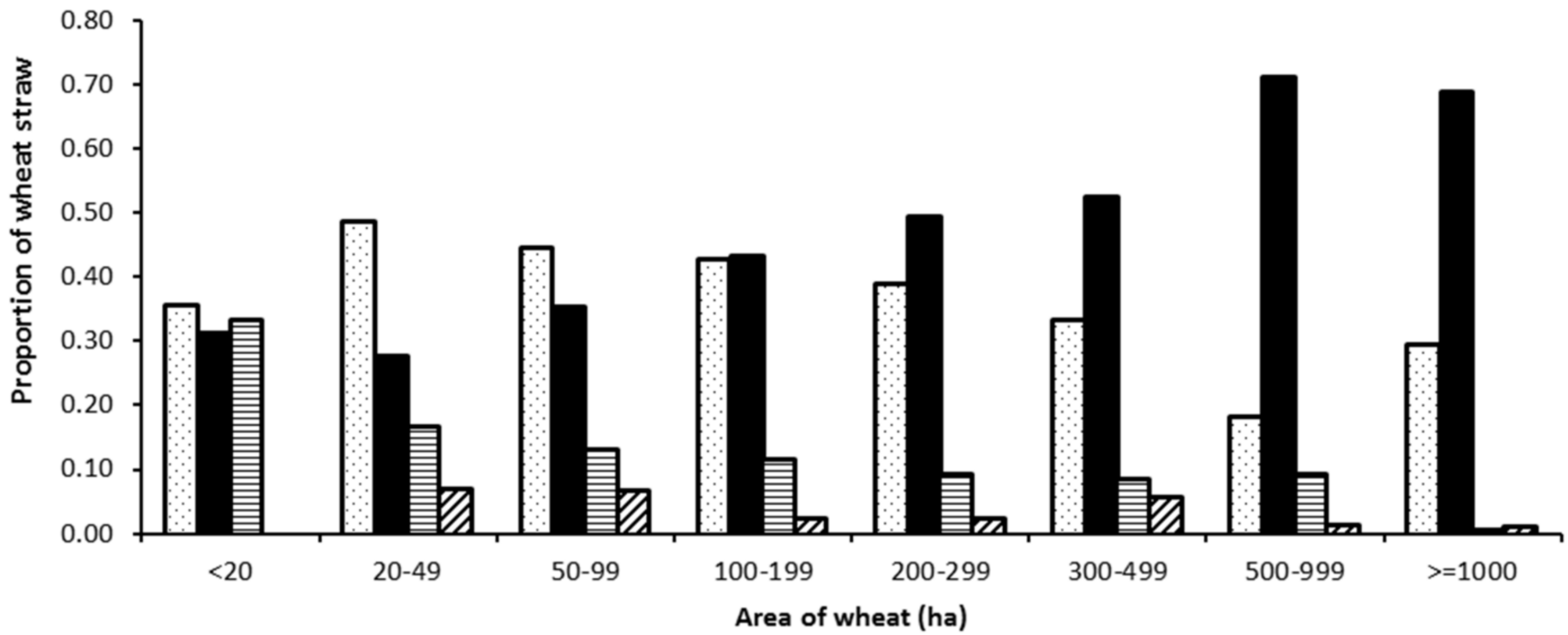


Figure 6.7: Mean percentage uses of straw for groupings based on the area of wheat grown. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).

6.5.4.3 Farmer age

The use of straw by each age category is given in **Fig. 6.8**. 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.

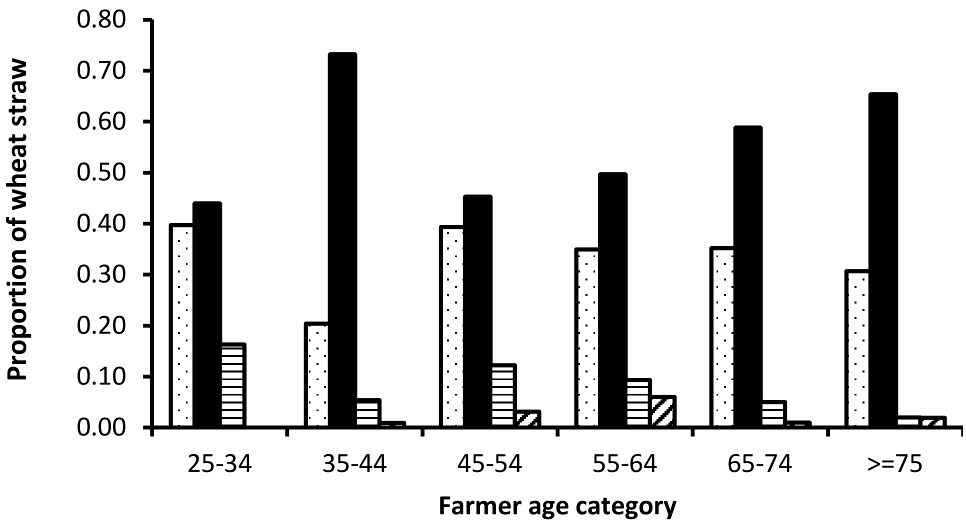


Figure 6.8: Mean percentage uses of straw farmer age categories. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).

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; **Fig. 6.9**) 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; **Fig. 6.9**) 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).

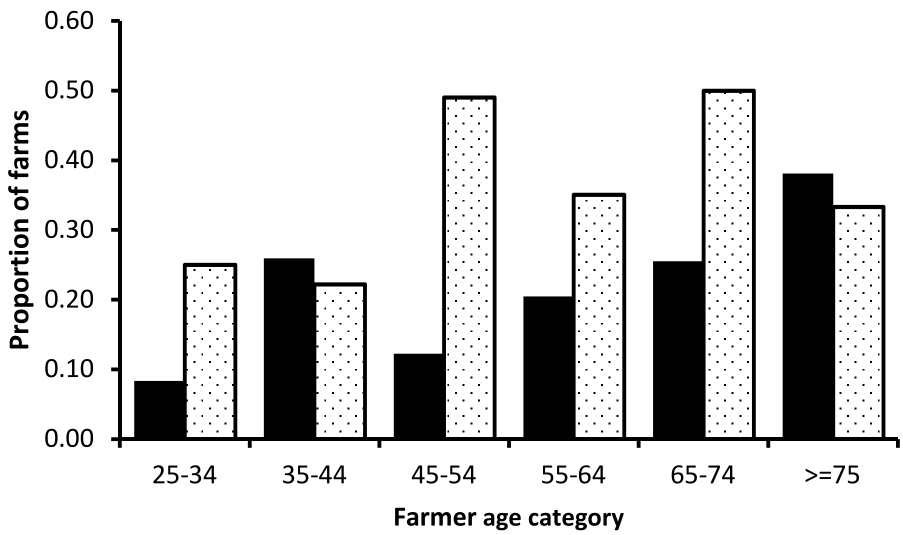


Figure 6.9: The proportion of farms that chopped and incorporated all or no straw in 2012 for different farmer age categories. Farms chopping and incorporating all straw (solid bar); farms chopping and incorporating no straw (dotted bar).

6.5.4.4 Farm type

The use of wheat straw for each farm type is given in **Fig. 6.10**. 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.

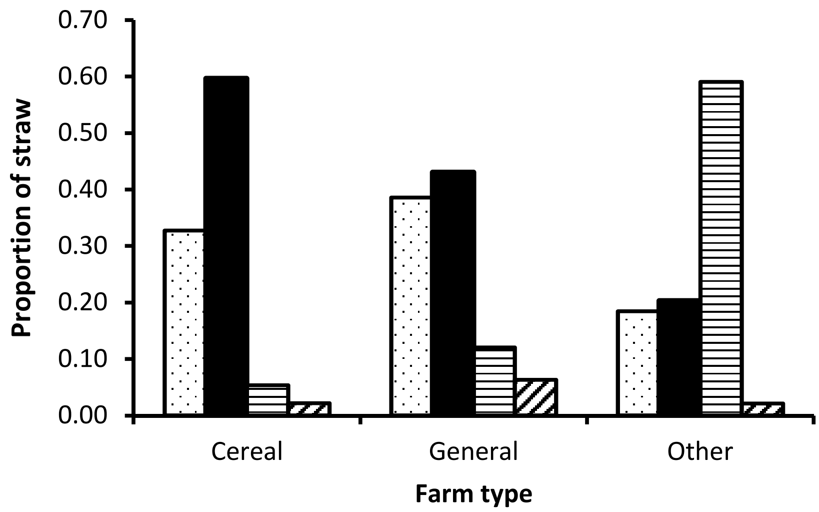


Figure 6.10: Mean percentage uses of straw for three farm types. Straw use: Straw sold (dotted bars); straw chopped and incorporated (solid bars); straw baled for on-farm use (horizontally-lined bars); straw used for other purposes (diagonally-lined bars).

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; **Fig. 6.11**) 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; **Fig. 6.11**) 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).

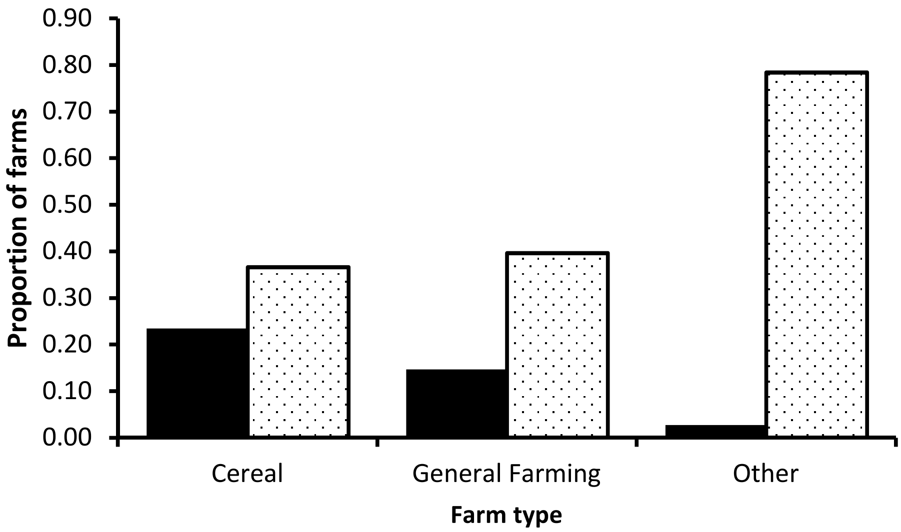


Figure 6.11: The proportion of farms that chopped and incorporated all or no straw in 2012 for each farm type. Farms chopping and incorporating all straw (solid bar); farms chopping and incorporating no straw (dotted bar).

6.5.5 Wheat straw management

6.5.5.1 Price for managing (Question 11)

Over half (276, 53.5%) of the respondents provided a price for 1 t 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).

Demonstrating the different ways that straw is sold and price is understood, some farmers gave prices per bale, in swath, per hectare or acre, or minimum prices or ranges of prices, e.g. £60+, £60-70 (in these cases, the lowest value was used in the analysis). Some respondents said that it would depend on other factors, such as fertiliser price. Other respondents said they would manage the straw at a certain percentage of the price offered for grain. This ranged from 50% to equal that of the price of grain (in these cases, the price of grain was assumed to be £155 t^{-1}, based on Nix, 2013).

The average price given was £90.86 but there was a large range of prices (**Fig. 6.12**). There were a number of very low values (e.g. £10, £15), which were lower than estimated breakeven prices for straw (see **Chapter 3**). 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.

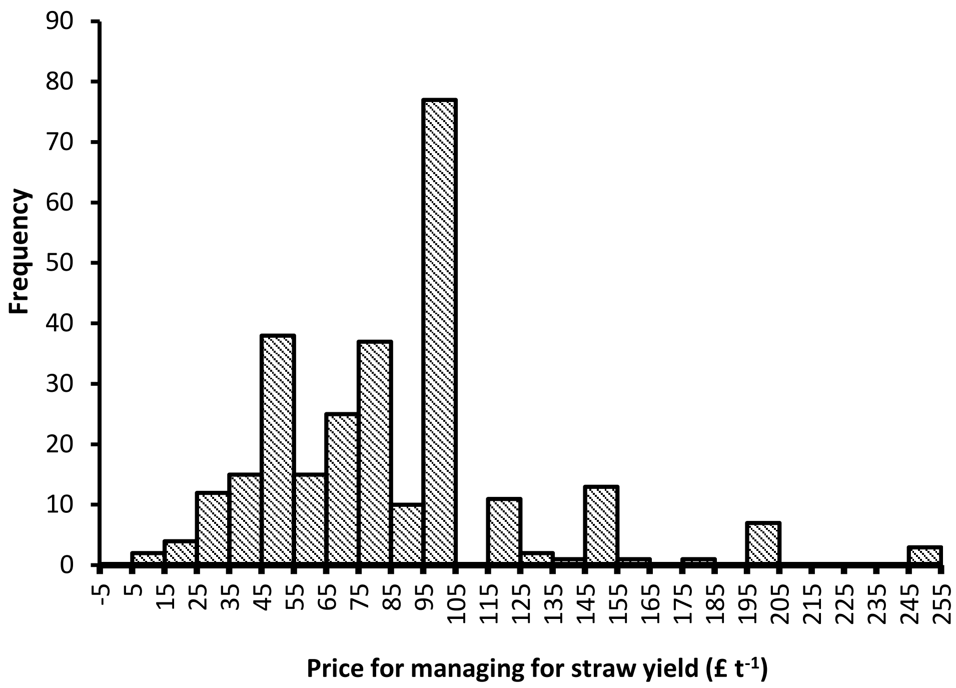


Figure 6.12: Frequency chart of prices for managing straw. (N.B. One value for £500 and one for £1,000 are excluded from the analysis.)

6.5.5.2 Selling extra straw (Question 12)

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. 6.13**). 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.

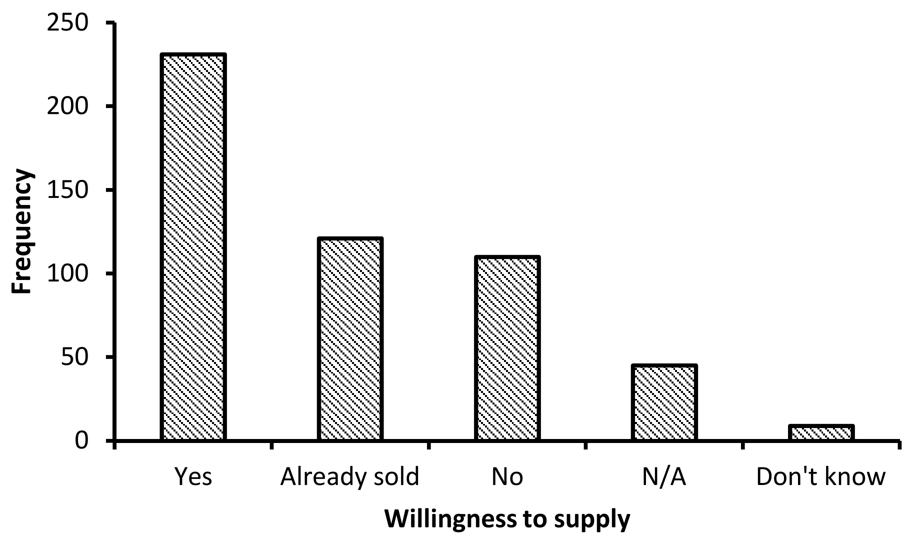


Figure 6.13: Willingness to supply extra straw at £100 t^{-1}. N/A = not answered

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 ($\chi_{(2)}$ = 3.71, *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 ($\chi_{(10)}$ = 3.30, *P* = 0.654) or farm size ($\chi_{(8)}$ = 12.07, *P* = 0.148). Willingness to supply extra straw did not significantly vary with region ($\chi_{(4)}$ = 8.40, *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.

6.5.5.3 Managing for straw yield (question 13)

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. 6.14**. It is informative to note that 91% of respondents wanting to manage for extra yield rate HGCA RLs as important or very important in question ten.

The intention to utilise new management practices did not relate to farm size ($\chi_{(32)}$ = 37.69, P = 0.225), farm type ($\chi_{(10)}$ = 3.76, P = 0.958), farmer age ($\chi_{(20)}$ = 18.54, P = 0.552), and region ($\chi_{(16)}$ = 20.22, P = 0.211). When incorporating the counts for N/A into the 'None' category, region does become significant ($\chi_{(16)}$ = 29.11, P = 0.023) with the East of England more likely to not use any management practices. However, farm type ($\chi_{(8)}$ = 9.70, P = 0.287), age group ($\chi_{(20)}$ = 18.14, P = 0.578), and farm size ($\chi_{(32)}$ = 40.88, P = 0.135) remain non-significant.

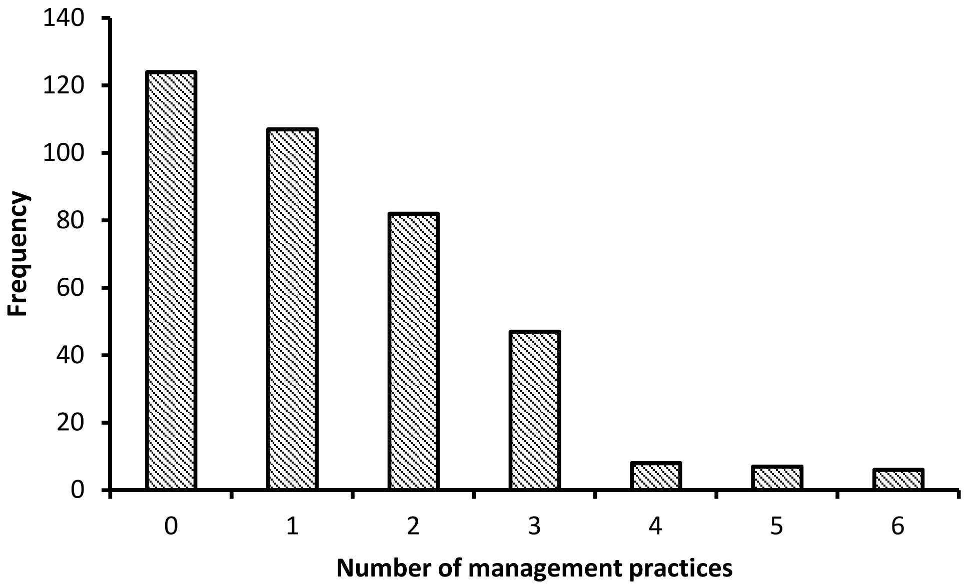


Figure 6.14: Number of management practices respondents would use to increase straw yield should the price reach £100 t^{-1}.

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. 6.15**). 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 ($\chi_{(40)}$ = 27.37, *P* = 0.936), farmer age ($\chi_{(25)}$ = 8.16, *P* = 0.999), farm type ($\chi_{(8)}$ = 10.98, *P* = 0.203), and region ($\chi_{(20)}$ = 21.31, *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.

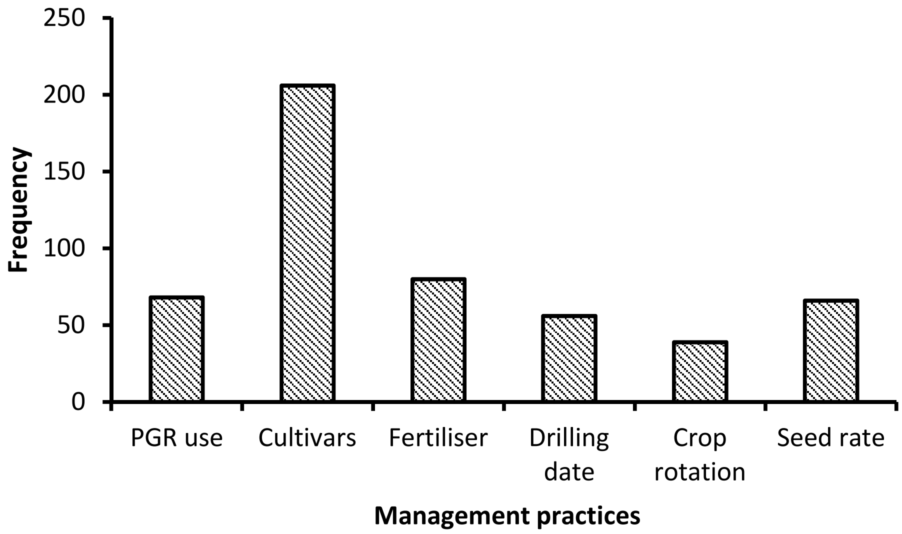


Figure 6.15: Number of respondents who would utilise each management practice.

6.5.6 Attitudes and opinions to straw use

6.5.6.1 Straw and attitudes

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 ($\chi_{(6)}$ = 14.19, 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 (**Table 6.14**). 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.

Table 6.14: Average rating and chi-square analysis results for farming objectives for those willing to sell extra straw, those who already utilise all of their straw, and those unwilling to sell more straw.

Farming objective	Unwilling	All used	Willing	Chi	P
Land stewardship	4.21	3.92	3.96	11.94	0.018
Maximising yields	4.56	4.45	4.47	3.39	0.495
Maximising gross margins	4.68	4.71	4.69	2.09	0.719
Maintaining the environment	4.21	4.01	4.06	7.92	0.094
Profit maximisation	4.53	4.56	4.56	2.55	0.636
Quality of life	4.37	4.23	4.32	11.94	0.018
Leisure and work balance	3.95	3.89	3.88	1.24	0.871
Family objectives and succession	4.23	3.77	3.97	14.51	0.006
D.f. = 4					

6.5.6.2 Comments

The survey provided an opportunity for farmers to comment about their decisions regarding straw use and these are presented in **Table 6.15**. The responses mainly supported the aspects discussed in the literature review though there were a few aspects mentioned that are interesting.

Table 6.15: A selection of comments and opinions, both positive and negative, regarding straw supply from the survey responses. Statements in quotation marks are direct quotations from survey responses whilst other comments are the interpretation of responses.

Aspect	Positive or negative	Key points and examples
Organic matter	Negative	Belief that organic matter must be returned to the soil. "Long term, land will only remain in good health if organic matter is not lost."
Long-term considerations	Negative	"[I] wish to look after the farm and manage it for the long term and am not chasing every last penny on gross margins to create a short term profit"; "Long-term, I think soil structure will suffer."
Timeliness	Negative	"It could cost far more if field operations are compromised by straw lying out on fields."
Experience	Negative	Respondent had conducted on-farm experiments and found better yields following incorporation. Respondent made the decision to chop and incorporate wheat straw and saw benefits after 5 years.

Aspect (cont'd)	Positive or negative (cont'd)	Key points and examples (cont'd)
Min- or no-tillage	Negative	Baling can cause timeliness issues and soil compaction for these types of system.
Replacement nutrients	Negative	Willingness to bale depends on price of fertiliser. Uncertainty about the amount of fertiliser required to replace that removed in straw.
Uncertainty about impacts	Negative	"We have sold straw for 3 years and ask ourselves, 'is it worth it?' every time!"
Rotations	-	The impact of straw removal depends on the crop rotation. "I currently only sell wheat straw if it benefits the next crop"
Short-term considerations	Positive	Not important if on a short-term tenancy, "I farm on short term tenancies. If I could obtain longer term agreements I would consider more incorporation of straw. As it is I take every pound that's going. I would bale every acre for £100 tonne^{-1} in bale".
Capacity	Negative	The amount of straw that could be supplied is limited by equipment, labour and storage capacity.

Aspect	Positive or negative (cont'd)	Key points and examples (cont'd)
Increasing straw yields	Negative	Concerns about increased lodging, combine speed reductions, and other harvesting issues.
	Positive	Increasing straw yields is feasible and currently practiced by some respondents. "Any opportunity to improve margins with good farming practice must be looked at." "We would consider triticale as an alternative to wheat if straw production became an objective."
Weather	Negative	Concerns about the weather restrict straw supply. "Wet weather at harvest is too much of a risk in allowing more than 50 % of the cereal area to be baled at nearly any price." "The last thing I need is more heavy machinery running over the fields, especially with increasing wet summers and autumns." "Any contractor requiring a large area to bale to make it worthwhile them coming, so exposing the farm and following operations to the weather as this year has shown."
Livestock	Negative	Biofuels will increase straw price for livestock producers; "[at £100 t^{-1} straw] cows would not be bedded up as often." "We as livestock farmers, obtaining straw from arable neighbours are now having to compete with Drax [straw-burning at power station], which has pushed up our costs […] considerably."
Contractors	Negative	Concerns about not having control of their farming operations, "…don't like being dependent on contractors."

Aspect (cont'd)	Positive or negative (cont'd)	Key points and examples (cont'd)
Gross margins and	Positive	"[If there was a market for straw] no one can afford to turn down extra profit."
	Negative	"We would only sell wheat straw if we could not make a living without." "Straw is too valuable to sell."
Biofuel	Negative	Respondents suggested biofuels are an unproven technology so their effectiveness is unknown; carbon sequestration in soil through incorporation is a better use of straw in combating climate change; and it is pointless using organic material when GHG emissions would result from producing fertilisers to replace exported nutrients. "Straw is scare enough without using it for inefficient biofuels. Such use of straw and wheat will stop livestock production in the UK." "The use of straw for biofuel is likely to push up the price of straw for livestock feeding/bedding."
	Positive	There was support for supplying straw for bioenergy. "…the idea for bioenergy is good news." "I believe strongly in alternative energy and in particular biomass."
Straw as a resource	Positive	"I am not an enthusiast of the straw chopper and thick cereal straw is a resource which should be fully utilised."

6.6 Discussion

Approximately 25% of the questionnaires were returned and suitable for analysis. The nonresponse assessment and knowledge of previous surveys suggest that there was bias in the responses to larger, commercially-minded farms. There was a large range of answers reflecting the considerable variability in almost all aspects of farming. With the self-administered questionnaire there is a risk that questions may have been misinterpreted by the respondents; hence caution is required when interpreting the results. However, there are a number of key findings which are considered below.

6.6.1 Wheat cultivars

As expected, the number of wheat cultivars grown increased with farm size and the area of wheat grown. The majority of farmers grew more than one cultivar at a time; growing more than one cultivar offers the possibility of increased profits and lower risk (Barkley & Peterson, 2008; Barkley et al., 2010). On average cultivars are changed every two to three years. Both the number of cultivars grown and the frequency of change suggest that a DPC could be included in the rotation and used only when the farmer wants to bale the straw.

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. HGCA 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.

6.6.2 Current straw supply

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.

More straw was baled for on-farm use in 2010 than 2012. However, differences between the sample frames of the studies exist with the current study sample frame biased towards larger farms and this, in part, explains differences in results. This is because choices about the amount of straw chopped and incorporated are determined by a number of factors, in particular 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. (2013a) 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.

It is unclear from the survey results whether more straw was chopped in 2012 because of lower demand or farmers were less willing to supply straw. It was clear that a number of respondents would have supplied more straw but for the wet weather. Some respondents said they would only sell straw in dry autumns, suggesting they would be unwilling to sign up to supply contracts that hold them to supplying straw regardless of the weather conditions. Because running a bioenergy facility at below capacity is likely to be economically unfeasible, the capacity of bioenergy in the UK must be determined by the minimum availability of straw. Scarlat et al. (2010) suggested basing bioenergy capacity on the minimum amount of feedstock available in an area.

6.6.3 Increasing straw yield

The average price 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. As **Chapter 2** demonstrates, 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, as discussed in **Chapter 2**, 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. Therefore, more work is needed to investigate this.

If increased straw yields are a goal of farmers then growing triticale (x *Triticosecale*) could be an option. Several respondents said they would grow it if straw reached £100 t^{-1}. Work has shown that triticale grain has benefits as feedstock for FGB production (Davis-Knight & Weightman, 2008) and the straw has benefits as feedstock for SGB production (reviewed in McGoverin et al., 2011). Ongoing work funded by the HGCA (HGCA, 2012) has found higher grain and straw yields for triticale compared to wheat.

One aspect that might make farmers less likely to manage for straw yields is the types of contracts for supplying straw for biofuels. Glithero et al. (2013b) respondents would prefer to commit to contracts for straw by area rather than weight. This would not provide an incentive to increase straw yield. Selling by area facilitates planning decisions as well as reducing uncertainty for farmers as to how much of their crop they would need to bale.

6.6.4 Future straw supply

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. It is recognisable that short-term and long-term considerations about soil quality differed. One respondent discussed that as a tenant farmer the long-term impact on the soil quality is of no concern to him so he would bale as much as possible. Other respondents were discussing the long-term effects and were incorporating straw for the long-term benefits.

Some respondents were strongly against the use of straw for biofuels. Many respondents who had livestock voiced concerns about potential increases in costs resulting from the use of straw for bioenergy, whilst respondents without livestock were also concerned about the impact on livestock farmers. It is unclear if work has considered whether the price farmers are willing to sell their straw for varies with end-use but it is possible that antagonism to biofuels might mean farmers need to be paid more for their straw. Therefore, willingness to supply for other uses might not be a good proxy for willingness to supply for biofuel production.

Some respondents mention how they would increase the amount of straw they sell if the price was higher than that for replacement organic matter, such as manure. But if the market for wheat straw increases then it is likely that the price of manure will also increase. Farmers might be more willing to supply straw for biogas production from anaerobic digestion as the solid by-product (biofertiliser) can be returned to the field.

One aspect that came up was uncertainty about soil impacts from removing the straw. For instance there was uncertainty about how much fertiliser would be required to replace that being removed in the straw, and the price of replacement fertiliser. Copeland & Turley (2008) suggest that some farmers are selling straw below breakeven price because they are unsure of the value of the nutrients being removed. Information is provided to farmers about amount of replacement fertiliser that would be required (e.g. HGCA, 2009; RB209, 2010) but it is argued that a more up-to-date data source is required showing variability in these fertiliser amounts as well as the price of fertiliser. More information about nutrient offtake for nutrients other than potassium and phosphorus is needed to facilitate decision making. Also, more information needs to be made available to farmers about the potential impacts on the soil quality from the removal of straw. Some respondents were unsure whether or not straw removal would impact on their soil quality; being more certain could help optimise straw supply. This information could also provide a methodology for testing soil so that farmers can be certain they are not impacting negatively on soil characteristics such as nutrient and SOM content. There is also uncertainty about the interaction between soil management practices; respondents who practice minimum- or no-till soil regimes believed that extra traffic from baling would cause compaction issues so should not be practiced. However, one suggestion by a recent report on residue availability (Malins et al., 2014) is that no-till soil management can mitigate the negative effects on soil organic carbon from residue removal. More research is needed and greater information needs to be provided to farmers.

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 (see **Chapter 4**) 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. This is already seen; one Lincolnshire livestock farmer complained about the extra cost of straw because of demand from straw-burning at Drax power station. As mentioned in **Chapter 3**, planning permission for one straw-burning facility has been turned down because of concerns about its impacts on the price of straw for other straw-users. Increases in costs for livestock farmers could put pressure on their businesses. It could also have an influence on animal welfare as straw has been shown to be important for pig and cattle welfare (Tuyttens, 2005); one respondent suggested that they would use less straw for their cattle if the price of straw was £100 t^{-1}.

6.6.5 Survey method

The sample frame in this study differs from Glithero et al. (2013a, b), which was based on the Farm Business Survey and is, therefore, representative of English farmers. However, similarities between the studies support conclusions of the current survey.

The survey responses might not accurately reflect decisions should the technology develop. When The Theory of Planned Behaviour (Ajzen, 1991) is applied to agriculture, it is noted that farmer behaviour could be based on other farmers' behaviour (the subjective norm) and the expected efficacy of carrying out the behaviour (perceived behavioural control; Burton, 2004). Once early adopters are carrying out the behaviour it might lead to a greater number of farmers carrying out the behaviour (subjective norm). As SGB production has not started yet, farmers have yet to see the efficacy of it for its goals of reducing CO_2 emissions and reduced reliance on foreign oil; having this demonstrated to them might mean they become more likely to be willing to supply straw (perceived behavioural control). Therefore, studies investigating the potential future supply of straw must bear this in mind when coming to conclusions.

6.7 Conclusions

The main findings of this chapter are:

- Of the wheat produced in 2012, 55% of straw was chopped and incorporated.
- If the price of straw were to increase to £100 t^{-1}, 49% of respondents would sell extra straw. The respondents who were unwilling to sell the extra straw represented 29% of the total amount of chopped and incorporated straw.
- The average price respondents wanted before managing for extra straw yield was £90.86 t^{-1} and the most widely selected method for increasing yield was growing cultivars with higher straw yield.

Chapter 7: Discussion

7.1 Introduction

The main purpose of this investigation was to assess the attributes beneficial to cellulosic biofuel production of current cultivars and determine how beneficial these traits would be. A farmer survey then considered current and future straw supply. This chapter brings together the key findings from this work and provides recommendations for different stakeholders in the production of SGBs from wheat straw.

7.2 Key findings

7.2.1 Straw yield and digestibility

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.

Straw digestibility differed significantly between two of the cultivars assessed. Only one of the cultivars, Cordiale, had digestibility assessments from the previous field experiments (Roy, 2014). This means that it is not possible to see if the significant differences between cultivars seen in the 2011-2012 field experiment were also present in the other field experiments.

7.2.2 Other dual-purpose cultivar traits

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.

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.

7.2.3 Benefits of dual-purpose cultivars

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. In particular, farmers on mixed-farms who want to avoid buying in straw might be interested in increasing straw yields, in particular when they have the option to return the nutrients to the fields in the form of livestock manure.

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, 2009a). However, the problem with 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 SOC from the removal of crop residue, then the benefits of increased straw yield would become more apparent.

7.2.4 Straw supply

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.

7.3 Biofuel production in the UK

Although there has been considerable progress in the development of SGB technologies, and commercial-scale production has begun in some places, it is unclear what the future holds for biofuel production in the UK. Further development of the bioenergy sector will require sufficient amounts of feedstock but, as suggested in this project, it is likely that availability of straw is overestimated which may limit any future progress.

7.3.1 Biorefinery capacity

As well as uncertainty over feedstock availability, biorefinery capacity may also limit progression of the bioenergy sector in the UK. The optimum feedstock demands often cited in the literature (e.g. 750,000 t yr^{-1}) represents a figure three times as large as the current and planned straw-burning power plants. Considering the difficulties that these companies have faced gaining planning permission at the lower feedstock demand plant size, a biorefinery of a greater size would unlikely to be granted planning permission. Thus, if the examples in the literature are representative, the plants in the UK will be unable to run at optimum capacity. Alternatively, the Crescentino plant in Italy has a much lower feedstock demand (270,000 t yr^{-1}), which is more representative of what is possible in the UK. Hence if this proves feasible, it could provide a blueprint for biofuel production in the UK.

Another aspect that might increase the feasibility of large-scale production is the pre-processing of material. Through processes such as densification, the transport costs for straw can be reduced and straw can be transported from much further away. This negates the need for locating the plant where enough straw can be collected without influencing current local straw markets. However, this would require further investigation, potentially via modelling approaches, as the increased distance is likely to negate any benefits of the densification process.

7.3.2 Digestibility

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).

7.3.3 Other bioenergy options

The future of energy might lie in further expansion of the straw-burning power plant capacity. Another area of renewable energy that is being pursued is anaerobic digestion (AD). It is interesting to note that the biogas yields from anaerobic digestion of wheat straw vary with straw characteristics (Motte et al., 2014), which suggest that research into the breakdown of straw for biofuel production might be similar to that for AD and, therefore, the cultivars found to be well suited for biofuel production might also be well suited to AD. AD might also be favourable in that the digestate from the process can be returned to farmland, providing nutrients and potentially increasing SOM. Some respondents of the farmer survey stated that they would supply wheat straw, but only if another source of organic material was returned to the farm. This suggests that farmers may be more accommodating to the idea of AD than biofuel production or the burning of wheat straw; providing another application of this kind of work.

7.3 Recommendations

7.3.1 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 (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 nitrogen 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).

7.3.2 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.

7.3.3 Biofuel producers

As mentioned previously, 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.

7.3.4 Home Grown Cereals Authority

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, the economic analysis suggested it was less valuable than the other cultivars. Further work is needed to identify the most appropriate cultivars for use as DPCs. The farmer survey suggests that the recommended lists produced by the HGCA are 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).

Uncertainty over soil impacts are also cited as a reason for not supplying straw. Therefore, quantifying sustainable removal rates is important, as well as developing straw collection methods that minimise impacts on the soil. Providing information on the nutrients being removed in straw could provide a solution. This may require studies to investigate the relationships between cultivars, or the current soil nutrient profile, and the amount of nutrients that are being removed. This information will enable more informed decisions on sustainable rate of removal of straw and may prevent surplus residue from being left on the field, which could be used by a biorefinery.

7.3.5 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.

7.4 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 author’s 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.

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Appendices

1. Field trial plan (2010-2011)
2. Field trial management plan (2010-2011)
3. Field trial plan (2011-2012)
4. Field trial management plan (2011-2012)
5. Survey covering letter
6. Farmer survey
7. Farm type characterisation

1. Field trial plan (2010-2011)

B1	D	B 1	C 2	G 3	Q 4	S 5	A 6	H 7	R 8	M 9	MW 10	In 11	Is 12	X 13	Z 14	Gl 15	D	Continued on following page
B2	D	X 31	Q 32	H 33	R 34	Gl 35	B 36	Is 37	S 38	In 39	G 40	Z 41	MW 42	M 43	C 44	A 45	D	Continued on following page
B3	D	Is 61	In 62	S 63	Z 64	M 65	H 66	G 67	C 68	R 69	B 70	A 71	X 72	Q 73	Gl 74	MW 75	D	Continued on following page

Number refers to plot number

Blocks: B1 = block 1; B2 = block 2; B3 = block 3

Cultivars: C = Cordiale; G = Grafton; X = Xi19; D = discard (c.v. Oakley)

PGR treatments: - = no chlormequat applied; + = chlormequat applied

Nitrogen treatments: no shading = N1 (final split of 0 kg ha^{-1} N); light shading = N2 (final split of 0 kg ha^{-1} N); dark shading = N3 (final split of 0 kg ha^{-1} N)

Continued from following page	D	MW 16	A 17	Is 18	C 19	R 20	Q 21	Z 22	S 23	B 24	Gl 25	In 26	X 27	G 28	M 29	H 30	D
Continued from following page	D	Z 46	H 47	X 48	Is 49	A 50	Gl 51	G 52	MW 53	M 54	Q 55	R 56	S 57	B 58	In 59	C 60	D
Continued from following page	D	Z 76	S 77	C 78	H 79	Q 80	R 81	B 82	X 83	G 84	In 85	M 86	Gl 87	A 88	Is 89	MW 90	D

2. Field trial management plan (2010-2011)

Action	Date	Description
Previous crop		Winter oats
SNS N Index	09/09/2010	32.9 kg ha^{-1}, SNS Index 0
Soil Indices		P:4, K:3, Mg:4, pH:7.2
Cultivations	16/09/2010	Plough
	11/10/2010	Power harrow
	14/10/2010	Roll after drilling
Crop/variety		Various
TGW (g)		Various
Sowing	13/10/2010	
Seed rate (m^{-2})		250 seeds m^{-2}
Drill type		Wintersteiger
Row width (cm)		12.5
Plot length (m)		24
Plot width (m)		1.625
Fertiliser	08/03/2011	87 kg ha^{-1} 34.5% Nitram (30 kg ha^{-1} N)
	08/03/2011	Human Extra @ 1 L ha^{-1}
	25/03/2011	Human Extra @ 1 L ha^{-1}
	06/04/2011	232 kg ha^{-1} 34.5% Nitram (80 kg ha^{-1} N)
	20/04/2011	Human Extra @ 1 L ha^{-1}
	06/05/2011	174 kg ha^{-1} 34.5% Nitram (60 kg ha^{-1} N)
	24/05/2011	Magnor @ 1 L ha^{-1}
Herbicide	08/03/2011	Hatra @ 1 L ha^{-1} + Picona @ 1.7 L ha^{-1} + Biopower @ 1 L ha^{-1}
	24/05/2011	Spitfire @ 1 L ha^{-1}
Fungicide	25/03/2011	Alto Elite CTL @ 0.75 L ha^{-1} + Vegas @ 0.15 L ha^{-1}
	20/04/2011	Proline @ 0.5 L ha^{-1} + Alto Elite @ 0.5 L ha^{-1}
	24/05/2011	Comet @ 0.5 L ha^{-1} + Justice @ 0.1 L ha^{-1} + Proline @ 0.5 L ha^{-1}
	15/06/2011	Caramba @ 0.75 L ha^{-1}
Insecticide	08/03/2011	Permasect @ 0.25 L ha^{-1}
	15/06/2011	Aphox @ 0.25 ka ha^{-1}
PGR	25/03/2011	Adjust @ 1 L ha^{-1} to +PGR plots only
	20/04/2011	Adjust @ 0.8 L ha^{-1} to +PGR plots only
Harvest	09/08/2011	Combine

3. Field trial plan (2011-2012)

B1	D	G-	C-	X-	C+	G+	X+	D	X+	G+	C+	X-	C-	G-	D	G+	C+	X+	C-	G-	X-	D
		1	2	3	4	5	6		7	8	9	10	11	12		13	14	15	16	17	18	
B2	D	X+	G+	C+	C-	X-	G-	D	X+	C+	G+	C-	G-	X-	D	X+	G+	C+	G-	C-	X-	D
		19	20	21	22	23	24		25	26	27	28	29	30		31	32	33	34	35	36	
B3	D	C+	X+	G+	X-	G-	C-	D	C+	G+	X+	G-	C-	X-	D	G-	X-	C-	X+	G+	C+	D
		37	38	39	40	41	42		43	44	45	46	47	48		49	50	51	52	53	54	

Number refers to plot number

Blocks: B1 = block 1; B2 = block 2; B3 = block 3

Cultivars: C = Cordiale; G = Grafton; X = Xi19; D = discard (c.v. Oakley)

PGR treatments: - = no chlormequat applied; + = chlormequat applied

Nitrogen treatments: no shading = N1 (final split of 0 kg ha^{-1} N); light shading = N2 (final split of 0 kg ha^{-1} N); dark shading = N3 (final split of 0 kg ha^{-1} N)

4. Field trial management plan (2011-2012)

Action	Date	Description
Previous crop		Winter Oats
SNS N Index	23/02/2012	18.9 kg ha^{-1}, SNS Index 0
Soil Indices		P:4, K:4, Mg:4, pH:7.6
Cultivations	13/09/2011	Plough
	22/09/2011	Power harrow
	06/10/2011	Roll after drilling
Crop/variety		Winter wheat: Cordiale cv., Grafton cv., Xi19 cv.; Oakley cv. (discard)
TGW (g)		Cordiale = 52; Grafton = 64; Xi19 = 37; Oakley = 56
Sowing	06/10/2011	
Seed rate (m^{-2})		250 seeds m^{-2}
Drill type		Wintersteiger
Row width (cm)		12.5
Plot length (m)		12
Plot width (m)		1.625
Fertiliser	24/02/2012	2.0 L ha^{-1} Headland Jet
	08/03/2012	116 kg/ha 34.5% Nitram (40 kg ha^{-1} N)
	20/03/2012	Headland Jett @ 2 L ha^{-1}
	11/04/2012	232 kg/ha 34.5% Nitram (80 kg ha^{-1} N)
	30/04/2012	Manganese 15% @1.5 L ha^{-1}
	10/05/2012	Various rates of N (see trial plan for rates)
	23/05/2012	Magnor @ 1 L ha^{-1}
	25/05/2012	Magnor @ 1 L ha^{-1}
Herbicide	09/11/2011	Liberator @ 0.6 L ha^{-1}
	20/03/2012	Lorate @ 25g ha^{-1}
	24/04/2012	Foxtrot @ 1 L ha^{-1} + Toil @ 1 L ha^{-1}
	23/05/2012	Spitfire @ 1 L ha^{-1}
Fungicide	20/03/2012	Opus @ 0.75 L ha^{-1} + Bravo @ 1 L ha^{-1} + Instinct @ 0.4 L ha^{-1}
	30/04/2012	Cortez @ 0.75 L ha^{-1} + Phoenix @ 1.3 L ha^{-1}
	23/05/2012	Opus @ 0.75 L ha^{-1} + Phoenix @ 1.3 L ha^{-1}
	25/06/2012	Orius @ 0.85 L ha^{-1} + Vegas @ 0.15 L ha^{-1}
Insecticide	09/11/2011	Permasect @ 0.25 L ha^{-1}
	25/06/2012	Aphox @ 0.28kg ha^{-1}
PGR	22/03/2012	Chlormequat @ 1 L ha^{-1} on +PGR plots only
	30/04/2012	Chlormequat @ 0.8 L ha^{-1} on +PGR plots only
Harvest	23/08/2012	Combine

5. Survey covering letter

Dear _____________.

I am currently studying at the University of Nottingham towards a PhD research degree. My project is funded by the Home Grown Cereals Authority and investigates the potential use of wheat straw to produce biofuel and how wheat varieties differ in their performance as a feedstock for biofuel production. As part of my project I am undertaking a survey of farmers to discover how a change in the market for wheat straw might influence their decision making. This work will contribute to understanding how a competitive biofuel industry in the UK could operate, and the impact of such a market on arable farmers.

Enclosed with this letter is a short survey that asks about your current farming practices, in particular with regard to wheat production and straw use. I am keen to get the views of all farmers regardless of their opinions on bioenergy and the potential use of straw for this purpose. Your answers are completely confidential and will be reported only as summaries in which no individual's answers or details can be identified. A box labelled with N/A is provided to the right of each question for you to tick if the question is not relevant or you do not wish to answer it.

The survey is anonymous; however, there is an opportunity to receive £200 of Marks and Spencer vouchers. If you wish to be entered into the draw please *provide your email or postal address at the end of the completed survey. This address will be deleted from our records after the draw has taken place and will not be supplied to a third party.*

If you have any questions or comments about this study, I would be happy to talk with you. My email address is toby.townsend@nottingham.ac.uk and my contact number is 01159 516081.

The results of this survey will be accessible on the completion of my PhD when a report will be provided to the HGCA (project code: 3741).

I realise that there are many other demands on your time, but I hope that you will be able to take just a few minutes to complete this survey. A pre-paid envelope is provided for you to return your survey to me. Your contribution to this research is very much appreciated.

Yours sincerely

Toby Townsend

6. Farmer survey

N.B. Farmer survey has been edited to fit the margins of the page.

Today's date:

Question 1 – In which county is your farm?

Question 2 – Do you grow wheat? (If you answer NO then please return the survey without answering the remaining questions.) [Choice of YES or NO]

Question 3 – What is the size of the farm (including any land under contract farming agreements)? (Please answer in either hectares or acres)

Question 4 – What area of the following crops did you grow for the 2012 harvest? (Please answer in either hectares or acres:

	Hectares	Acres
Wheat intended for milling		
Wheat intended for animal feed		
Winter barley		
Spring barley		
Oats		
Maize		
Sugar beet		
Oilseed rape		
Potatoes		
Beans/peas		
Bioenergy crops		
Grass		
Other (*please say*)		
Other (*please say*)		

Question 5- What livestock have you had on your farm in 2012?

	Average number on farm in 2012
Sheep (ewes)	
Sheep (other than ewes – e.g. store lambs)	
Dairy cows	
Suckler cows	
Store cattle, calves or other breeding cattle	
Poultry (hens, turkeys, broilers, other poultry)	
Pigs (breeding sows)	
Pigs (weaners bought for finishing)	
Other (*please say*)	
Other (*please say*)	

Question 6 – On average how frequently do you change the wheat varieties that you grow?

Every year	
Every 2-3 years	
Every 4-5 years	
Every 6+ years	

Question 7 – On average how many wheat varieties do you grow at a time?

1	
2	
3	
4	
5+	

Question 8 – How was the wheat straw from the 2012 harvest used? (Please answer in hectares or acres)

		Hectares	Acres
Sold as baled	for livestock		
	for industry, e.g. building materials		
	for bioenergy		
	third party unknown market		
Sold in swath	for livestock		
	for industry, e.g. building materials		
	for bioenergy		
	third party unknown market		
Chopped and incorporated			
Baled for on farm use			
Other (*please say*)			

Question 9 – How important do you consider the following characteristics when choosing wheat varieties? *Please rate the importance of each characteristic.*

	Very important	Important	Neutral	Unimportant	Very unimportant
Potential gross margins					
Grain yield					
Resistance to lodging					
Seed cost and availability					
Resistance to disease					
Crop timing constraints (e.g. sowing/harvest dates)					
Customer preferences and contractual requirements					
Other (*please say*)					
Other (*please say*)					

Question 10 - When selecting which <u>wheat varieties</u> to grow, how important are the following sources of information? *Please rate the importance of each source*

	Very important	Important	Neutral	Unimportant	Very unimportant
HGCA recommended lists					
Own knowledge and experience					
Agronomist					
Word-of-mouth (e.g. neighbouring farmers)					
Customer preference and contractual requirements					
Other (*please say*)					
Other (*please say*)					

Question 11- At what price for <u>wheat straw</u> (£ per tonne baled at the farm gate) would you start to manage your wheat for straw yields as well as grain yields?

Question 12 – Would you increase the amount of <u>wheat straw</u> you sell if you were offered one of the following?

- a guaranteed price of £100 per tonne of <u>baled straw at the farm gate</u>
- a guaranteed price of £162 for <u>1 hectare</u> (£65 for 1 acre) of wheat straw in swath

YES	
NO	
I already sell all my straw	

Question 13 – Would you use any of the following management practices to increase wheat straw yields if you were offered one of the following?

- a guaranteed price of £100 per tonne of baled straw at the farm gate
- a guaranteed price of £162 for 1 hectare (£65 for 1 acre) of wheat straw in swath

Please tick the relevant boxes and enter any additional management practices

Reduce plant growth regulator (PGR) use	
Select wheat varieties with higher straw yields	
Change fertiliser practices	
Drill earlier	
Change crop rotation	
Increase seed rate	
Other (*please say*)	
Other (*please say*)	

Question 14 – How important are the following objectives for your farm?

	Very important	Important	Neutral	Unimportant	Very unimportant
Land stewardship					
Maximising yields					
Maximising gross margins					
Maintaining the environment					
Profit maximisation					
Quality of life					
Leisure and work balance					
Family objectives and succession					

Question 15 – Have you had any diversification enterprises in 2012? *For example: agricultural contracting, processing or retailing farm produce, letting cottages, bed and breakfast, and livery. Please answer YES or NO. If you answer YES, please briefly mention what diversification enterprise(s) you have had.*

YES	
NO	

Question 16 – How long have you been the principal manager of the farm?

Question 17 – What is your age?

Less than 25	
25-34	
35-44	
45-54	
55-64	
65-74	
75+	

This is the end of the survey. A box is provided below if you would like to give any additional comments:

[Comments box]

Prize draw

If you would like to be entered into the prize draw please supply your postal address or email address in the box below.

7. Farm type characterisation

A number of assumptions were made regarding the livestock choices on the survey and the options in the characterisation.

Survey category	**Farm classification category**
Beans/peas	50% "Peas/beans (stockfeed)"; 50% "Peas/beans (human consumption)
Grass	"Grassland"
Bioenergy crops	"Other industrial"
Store cattle, calves or other breeding cattle	"Beef cows non LFA"
Suckler cows	"Heifers"
Sheep (ewes)	"Ewes non LFA"
Sheep (other than ewes – e.g. store lambs)	"Other sheep non LFA"
Pigs (breeding sows)	"Sows and gilts"
Pigs (weaners bought for finishing)	"Piglets"
Poultry (hens, turkeys, broilers, other poultry)	66.6% "Laying hens"; 33.3% "Broilers"