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The Renewable Energy Directive and Cereal Residues

Carly Whittaker[a*], Aiduan Borrion[ab], Linda Newnes[a] & Marcelle McManus[ab]

[a] Department of Mechanical Engineering, University of Bath, Claverton Down, Bath, BA2 7AY, UK

[b] Institute of Sustainable Energy and the Environment, University of Bath, Claverton Down, Bath, BA2 7AY, UK

*Corresponding author

Carly Whittaker: C.Whittaker@bath.ac.uk

Sustainable Energy Research Team,

Department of Mechanical Engineering,

University of Bath,

Claverton Down,

Bath,

BA2 7AY,

UK

Phone number: (+44) 01225 385 164

Keywords

Renewable energy directive, second generation biofuels, cereal straw, greenhouse gas emissions, straw removal

Research Highlights

- There is a high uncertainty in the range of possible GHG implications of removing straw.
- GHG emission savings for bioethanol from wheat straw are 90-92% compared to gasoline.

- GHG implications of straw removal can reduce the GHG savings to -43 to 84%.
- The GHG benefits of straw removal for bioethanol production exceed benefits from incorporation.
- Further research is required to understand SOC losses due to straw removal.

1. Abstract

The Renewable Energy Directive (RED) specifies that biomass feedstocks should be sustainable and are not directly implicated with conversion of areas of high carbon stock and biodiversity. There are concerns that first generation biofuels from food-based crops will lead to negative indirect impacts on food prices and place pressure on agricultural land. The RED incentivises the use of non-food and land biomass resources by awarding them with financial credits and assigning them a zero greenhouse gas (GHG) 'cost'. This paper questions whether there are any GHG implications with straw removal from soil that should be accounted for. The results are placed in context with the emissions from wheat straw-based bioethanol, which can achieve GHG savings of 90-92%. The direct GHG implications of straw removal from soil are highly dependent on changes in SOC and replacement of nutrients removed in straw. The results indicate that they have the potential to either be minimal (90% savings) or compromise the emission saving targets of straw-based bioethanol (-25% savings). The alternative option of incorporating straw into the soil could sequester between 3.6 and 26.5 tonnes $CO_{2\ eq.}$/ha over a 20 year period, whereas substitution of fossil fuels would avoid 35.6 tonnes $CO_{2\ eq.}$/ha. Understanding the full implications of straw removal relies on further research into the residue removal limitations and the impact that losses of SOC has on soil quality.

2. Introduction

2.1. The Renewable Energy Directive and second generation biofuels

The Renewable Energy Directive (RED) was developed in 2009 by the European Parliament and the Council of the European Union to promote the use of renewable energy resources by participating Member States (EC 2009). The UK is committed that by 2020, 15% of all consumed energy will be produced from renewable resources. At least two thirds of this will contribute towards mitigating greenhouse gas (GHG) emissions from transportation. The transport sector currently represent 20% of total UK GHG emissions (DECC 2011) and is one of the only sectors where GHG emissions have increased since 1990, where sheer increases in kilometres travelled have overcome any emission savings achieved by adoption of efficient fuels and vehicle efficiency improvements (EEA 2012). Biofuels are identified as a major short-to-medium-term solution for mitigating GHG emissions from transport (DTI 2007). Their advantage is that some can be manufactured today using existing technology, and can be used, at certain blends, in existing vehicles, and a distribution network already exists. There is debate, however, over the potential GHG emission savings that can be achieved by an increase in uptake of biofuels, and concerns over their sustainability has led to the need individually assess each biofuels' GHG mitigation potential (RS 2008).

The RED specifies that biofuels should be sustainable. It introduces broad sustainability criteria to ensure that no adverse land use change (LUC) occurs from sourcing biofuels from high carbon or biodiverse lands (EC 2009). It presents the main methodological framework in European renewable energy policy for assessing the GHG emissions from biofuel supply chains. The methodology mainly follows an attributional life cycle assessment (ALCA) approach, which provides information about the direct GHG emissions that are attributed to the production and use of a product (Sanchez et al. 2012). It is agreed that this methodology is best suited for GHG reporting and regulation as the operator has a greater deal of control over the direct emissions resulting from their product (Nuffield Council on Bioethics 2011). It is believed that consequential LCA, which examines the GHG emissions occurring due to a change in production of a product, is best suited for policy analysis (Brander, et al. 2009a; Nuffield Council on Bioethics 2011; Sanchez et al. 2012).

It is suggested that the RED is focused on sustainability issues associated with '1st Generation Biofuels' and is not yet prepared to account for emissions from '2nd generation biofuels' (Whittaker et al. 2011). Its aim is to address the negative indirect impacts that biofuels may have on food prices and direct and indirect LUC (RS 2008). Current targets for 2020 are to produce 10% of all consumed energy from biofuels, and there are proposals that only half of this can be from food-based resources (ICCT 2012). It incentivises the use of non-food and non-land biomass resources by awarding double financial credits and assigning a zero GHG 'cost' to these feedstocks. New proposals for the directive are to increase some feedstocks, including cereal residues, to quadruple credits (ICCT 2012). The

RED specifies that cereal residues are not attributed any GHG emissions from the upstream phases, a methodological practice which has been deemed "clearly incorrect" (Kindred et al. 2008). There can be confusion over what constitutes a co-product or residue or waste and this can significantly affect the overall GHG emission results (Gnansounou et al. 2009; Kaufman et al. 2010; Mendoza et al. 2008).

2.2. Co-Products, Residues, Wastes and LCA

Co-products and wastes are products that have an inelastic supply in response to demand (RFA 2010), as their rate of production is dependent on another product (Bauen et al. 2008). Residues are a special type of product that arise in agricultural or forestry systems, as there is an option to harvest them or leave on them onsite. Though the terms 'co-product', 'waste' or 'residue' may depend on the viewpoint of who must decide on how to use or dispose of a material, differentiating between them is a crucial issue in LCA (Whittaker et al. 2011). If a product is classified as a co-product, then it is necessary to determine the method in which the environmental impacts from upstream processes are allocated between co-products (CEN 2006a). If a product is classified as a waste, then it is generally assumed that disposal of this product will be attributed to the determining product (CEN 2006b).

In the United Kingdom, the Department of Transport's Renewable Transport Fuel Obligation (RTFO) provide a two-step process for biofuel producers to determine whether a co-product is a true co-product, or a by-product. By-products are considered to be minor, and are given the same status as a waste. The first step involves consulting a list of feedstocks that are identified as by-products. Straw is on this list (Dft 2012). Feedstocks not listed are classified as by-products if they represent less than 15% of the total financial output of the crop (Dft 2012). Feedstocks worth more than this are defined as co-products, and are allocated GHG emissions according to the method specified in the RED. Determining a product's status by its financial value means that some feedstocks may temporarily fluctuate between being co-products or wastes, and their GHG emission profile will be assessed completely differently in either case. This will constitute a risk to biomass producers who are committed to strict GHG saving targets. Also, the point at which the biomass is financially assessed may also cause confusion. To be precise, allocation should occur at the point of creation. In some cases, co-products do not become financially favourable until a after they have been processed into a more valuable form (Aylott et al. 2012). For example, cereal straw is defined as a by-product although it can be worth up to 19% of the total value of a wheat crop, even before baling (Whittaker et al. 2012).

As the RED does not attribute any upstream emissions from cereal cultivation to straw it implies there are no sustainability impacts associated with using it (Whittaker et al. 2011). This somewhat a contradiction of the European ‘Common Agricultural Policy’ which identifies cereal residues as an important contributor towards erosion control due to rainfall and wind (Louwagie et al. 2009) as well as being implicated with nutrient recycling, maintaining soil structure and regulating water retention (Lal 2008; Mondini & Sequi 2008). Indiscriminate removal can lead to a decline in soil quality, which can have both short and long-term adverse impacts on the environment (Lal 2005). Currently there are no requirements in GHG reporting methodologies to account for environmental impacts from removing straw from land.

2.3. GHG Implications of straw removal

A need for developing a soil quality indicator for use in LCA studies has been identified, as soil is a non-renewable resource that plays a central role in agricultural systems (Garrigues et al. 2012). There is on-going debate to the impacts of straw removal from soil (Cherubini 2010), and a few studies have placed these impacts in the context of a LCA study. The majority of studies examine impacts on soil quality; however there are large uncertainties in the results, and hence, there is currently no consensus (Cherubini 2010; Gabrielle & Gagnaire 2008). One study examined the impact of straw removal in the context of bioethanol production from wheat straw and found that net GHG emissions savings of 49% could be achieved (Cherubini & Ulgiati 2010). This fulfils the 35% GHG emission saving target set by the RED for installations established before January 2017 but would not reach the 60% target that must be met after January 2018 by installations that start on or after 1 January 2017. There are proposed changes to reduce the emission saving limits to 60% for plants initiating operation after 2014 (ICCT 2012). The results showed that the GHG implications of straw removal could represents at least 50% of the emissions of bioethanol production, suggesting that the GHG implications of straw removal may compromise the ability for straw-based bioethanol to achieve future RED emission saving targets.

2.4. The Aim of this Research

Three main sources of GHG emissions are suggested to be implicated with straw management: substitution of nutrients, changes in N_2O emissions from incorporation, and changes in SOC (Cherubini & Ulgiati 2010). This study addresses the sustainability implications with utilising cereal straw for 2nd generation biofuel production, and how these are accounted for under the GHG reporting methodology set out in the RED. The potential range of GHG implications from straw management are assessed according to literature estimates. There are various options in which to study the impacts of straw removal in a LCA context, hence, methodological issues are also explored. The results are placed in context of a recently published lignocellulosic bioethanol LCA study (Borrion et al. 2012) to test whether the impacts of straw removal compromises the ability of straw-based bioethanol from achieving GHG savings.

2.4.1. Nutrient substitution penalty

The 'nutrient substitution penalty' represents nutrient compensation after straw removal in order to avoid losses in grain yield (Punter et al. 2004). Conflicting evidence is found in literature on the impacts of straw management on wheat yield, with field trials showing both increases (Liu et al. 2011) and decreases (Limon-Ortega et al. 2008), but both without significance. Some estimates of nutrient off-take are deduced from analyses of the nutrient content of straw (CORN n.d.; NRCS n.d.) or biophysical models (Gabrielle & Gagnaire 2008). These may not represent nutrient availability in the field as the relatively high C:N ratios of cereal residues may lead to nitrogen immobilisation during decomposition and cause an increase in the nitrogen requirements for the following crop (Limon-Ortega et al. 2008). There can also be variation in nutrient contents of straws between sites and across years (Withers 1991).

2.4.2. Nitrous oxide emissions

The Intergovernmental Panel on Climate Change (IPCC) provides specific calculation methodologies for accounting for GHG emissions from a range of activities that take place in the agricultural sector, including exacerbated N_2O emissions from nitrogen fertilisation of soils. The IPCC assume an above-ground nitrogen content of 9g N/kg dry matter for wheat straw (De Klein et al. 2006), and incorporation of these residues leads to the release of N_2O emissions at a rate of approximately 140 kg $CO_{2\ eq.}$/tonne straw (ts).

Cherubini & Ulgiati (2010) calculated a net saving in N_2O emissions due to straw removal, and this has also been demonstrated in field trials (Liu et al. 2011; Malhi et al. 2006; Malhi & Lemke 2007).

2.4.3. Soil organic carbon

Soil can act as either a sink or source of carbon (Kindred et al. 2008). Soil organic carbon (SOC) is a key indicator of soil quality and degradation (Brandão et al. 2011; Garrigues et al. 2012), as it directly affects soil properties such as productivity, nutrient recycling and general soil physical properties (Powlson et al. 2008). Increases in SOC can potentially mitigate 89% of emissions from global agricultural systems (Smith et al. 2012). SOC sequestration occurs as a result of the long-term storage of atmospheric CO_2 as a relatively inert form of carbon with a potential residence time of decades to centuries (Kochsiek & Knops 2012; Lal 2008). SOC losses can occur due to oxidation of SOC after tillage operations; up to 15 kg C/ha during mouldboard ploughing (Lal 2004). Residue incorporation and reduced tillage can lead to a build-up of SOC over time, as more stable sources are left undisturbed and soil microbes tend to favour more readily available carbon sources (Kochsiek & Knops 2012).There are concerns that the removal of crop residues can lead to a decline in SOM, even less is taken than that required for effective erosion control (Lal 2005). A removal rate of 20-40% is believed to be sufficient to compromise soil health (Reijnders 2008). There has been an increased interest in including changes in SOC in LCA studies, however as of yet, there is no harmonised method (Brandão et al. 2011).

3. Methodology

3.1. LCA of lignocellulosic bioethanol production

A RED- compliant study of bioethanol production from straw is required in order to assess the impact of straw removal on the GHG saving potential. The final unit of measurement is 'one GJ bioethanol from wheat straw', and the functional unit is 1 GJ of biofuel distributed to an end-point, ready to be sold or blended. According to the RED, wheat straw is not attributed any emissions from cultivation, though this study performs allocation by energy content and price as part of a sensitivity analysis. A lower heating value of 13.1 GJ/tonne and 13.0 GJ/tonne (Whittaker et al. 2011) and a price of £113.8/tonne and £30/tonne is assumed for wheat grain and straw, respectively (Whittaker et al. 2012). Exported lignin is regarded as a 'residue from conversion' and is not attributed emissions from upstream events, however this is also allocated in the sensitivity analysis assuming a lower heating value of 9.72 GJ/tonne (Borrion et al. 2012) and a price of £250/tonne (Higson 2011). A price of £509.62/tonne (Dft 2006) and energy content of 26.11 GJ/tonne (Balat 2011) is assumed for bioethanol. A grain yield of 6.6 (standard deviation 3.34) tonnes/ha (Webbs et al. 2010) and straw yield of 2.5-5 tonnes/ha (Nix 2011) is assumed. A delivery distance of straw of 50km is assumed. Transport and landfill of slurry and gypsum is allocated 100% to bioethanol. Global warming potentials of 23 and 296 kg CO2 eq./kg are assumed for methane and nitrous oxide, according to the RED, and from this point on GHG emissions will be referred to as 'emissions'.

The bioethanol production process is based on a recently published study by Borrion et al (2012), which adapted a simulation system, based on the large-scale NREL corn stover to bioethanol process (Wooley et al. 1999), for wheat straw. The process is based on a very large-scale industrial plant, with an input rate of 106 tonnes/hour of wheat straw with 15% moisture content and output rate of 28 tonnes/hour bioethanol. The theoretical maximum yield of co-fermentation of both C6 and C5 sugars is 33 tonnes bioethanol/hour. If only C6 sugar is converted, a minimum output rate of 20 tonnes/hour bioethanol is achieved. A period of 8406 hours of operation time is assumed, which is equal to an annual production scale of 757152 tonnes of wheat straw on a dry basis. The study by Borrion et al (2012) is modified to be compliable with the GHG reporting methodology detailed in the RED as it previously allocated emissions by mass.

In the ethanol conversion process, the large energy inputs in pre-treatment, product recovery and enzyme production are due to the steam and electricity requirements. Steam is needed for pre-treating straw due to the high temperature requirement in subsequent enzymatic hydrolysis reactions. A large amount of electricity is required in the pre-treatment stage. It is assumed that lignin is treated onsite and combusted in a combined heat and power plant with a combined thermal input rating of 100 MW, and overall thermal efficiency of 85%. This provides all of the heat, however not all of the power requirements for conversion, therefore 122.3 kWh/tonne (bioethanol) of grid electricity is imported from the grid. The total electricity consumed is 4217 kJ/kg ethanol according to modified NREL study. The electricity generated from lignin based CHP is 4195 kJ/kg bioethanol. After the heat requirements for conversion are fulfilled 0.26 tonnes of excess lignin remain (Figure 1).

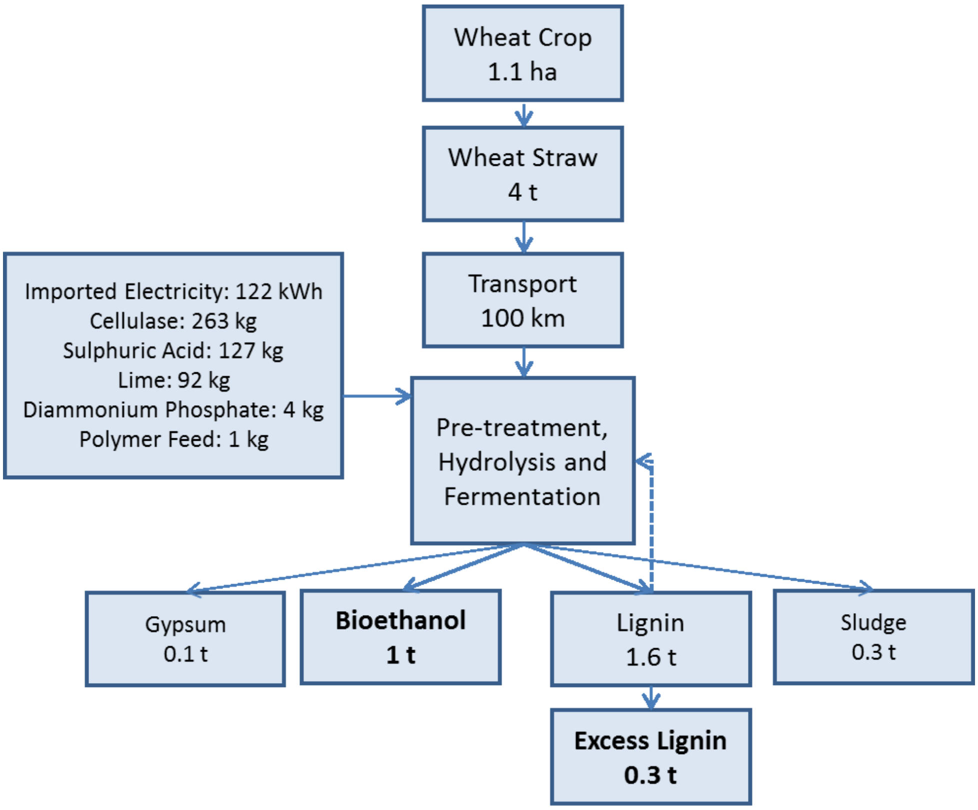

Figure 1 Process diagram for bioethanol production from wheat straw

3.2. LCA Methodology

3.2.1. Direct emissions and reference systems

The GHG implications of straw removal are assessed in a number of ways, but are measured in kg $CO_{2\ eq.}$/tonne straw removed (tsr). The main aim of the RED is to include the direct impacts of biofuels. The direct GHG implications of straw removal are considered, as shown below in Equation 1:

$$GHG_{SR} = SOC + GHG_{FM} + GHG_{diesel} \qquad (1)$$

Where SOC is the loss of SOC (kg $CO_{2\ eq.}$/tsr), GHG_{FM} is the total GHG emission resulting from fertiliser manufacture to compensate nutrient off-take, and GHG_{diesel} represents the emissions from baling straw.

Another methodology, described by Bird et al. (2011), is to consider the ‘forgone’ sequestration from incorporation by comparing the direct impacts of straw removal with a ‘reference system’ where straw is left onsite. (Equation 2, as modified from Cherubini & Ulgiati (2010)).

$$\Delta GHG_{SR} = \Delta SOC + GHG_{FM} + \Delta N_2O + \Delta GHG_{diesel} \qquad (2)$$

Where ΔGHG_{SR} represents the total change in emissions between straw removal compared to straw incorporation, including changes in soil carbon (ΔSOC), N_2O (ΔN_2O) and diesel consumed (ΔGHG_{diesel}).

3.2.2. Impacts of straw removal

A series of literature reviews were performed to determine changes in SOC due to straw incorporation, removal and nutrient off-take due to straw removal and straw chopping and baling. Emission factors are taken from the Ecoinvent Database for fertiliser manufacture (EcoInvent 2007). ‘N Fertiliser’ is based on ammonium nitrate, as this is the most widely used source of N in the UK (Thomas 2011). ‘P fertiliser’ is based on triple superphosphate, with a P_2O_5 concentration of 48%, and ‘K fertiliser’ is based on potassium chloride, or potash, with a K_2O concentration of 60% (Hillier n.d.).

IPCC Tier 1 methodology is used to calculate N_2O emissions from artificial fertiliser application and crop residue incorporation (Equation 11.6 in De Klein et al. 2006). The parameters used are listed in Table 1. The yield of the crop is based on data provided by (Webbs et al. 2010), which provides the average and standard deviation for wheat grain yields across the UK. It is estimated that 66% of the non-grain above-ground component of wheat can be removed by modern baling technology (Webbs et al. 2010).

Table 1 Parameters used for N_2O calculations.

Parameter	Best Guess	Standard Deviation/Range	Distribution
Crop T	6.6	3.34	Normal
Slope	1.61	0.02	Normal
Intercept	0.4	0.05	Normal
RG_{Bio}	0.23	0.136 - 0.324	Uniform
Emission factor for N addition to soil *	0.01	0.03 - 0.03	Uniform
Proportion of N leached from N additions	0.3	0.1 - 0.8	Uniform
Emission factor for leached N from N additions *	0.0075	0.0005 – 0.025	Uniform

Proportion of mineral N volatised	0.1	0.03 - 0.3	
Emission factor for volatisation from N additions *	0.01	0.002 – 0.05	Uniform

* Units are kg N_2O-N/kg N

3.3. Sensitivity and Uncertainty Analysis

The sensitivity of the GHG implications of straw management are placed in context with the GHG emissions from bioethanol production. The impact of allocation methods (energy and price methods) is also shown. The threshold GHG penalty for straw removal for current bioethanol from wheat straw to achieve 35%, 50% and 60% GHG savings are determined. An uncertainty analysis is performed to assess the range of uncertainty for each contributor to the emissions associated with removing straw. This is performed following a Monte Carlo analysis as described by Guo & Murphy (2012), with 1000 runs. The probability distribution of impacts was assumed to be ‘uniform’ unless otherwise stated. This is due to the lack of data on the likelihood of potential impacts. The consequences of this decision are discussed.

4. Results

4.1. Emissions from lignocellulosic bioethanol production

GHG emission savings of between 46% and 90% for lignocellulosic bioethanol are observed in literature (Borrion et al. 2012). This RED-compliant study has calculated a GHG saving of 90-92%. The effect of allocation on the results is illustrated in Figure 2. If emissions from the cultivation stage are allocated between wheat and straw, a GHG saving of 75-77% is achieved, if allocated by energy content, or 82-85% if by price. Allocating emissions between bioethanol and excess lignin does not affect the GHG savings as small quantities of lignin are produced. Therefore allocation decisions regarding the cultivation phase can have a potentially large impact on the calculated emission savings of residue-based bioethanol.

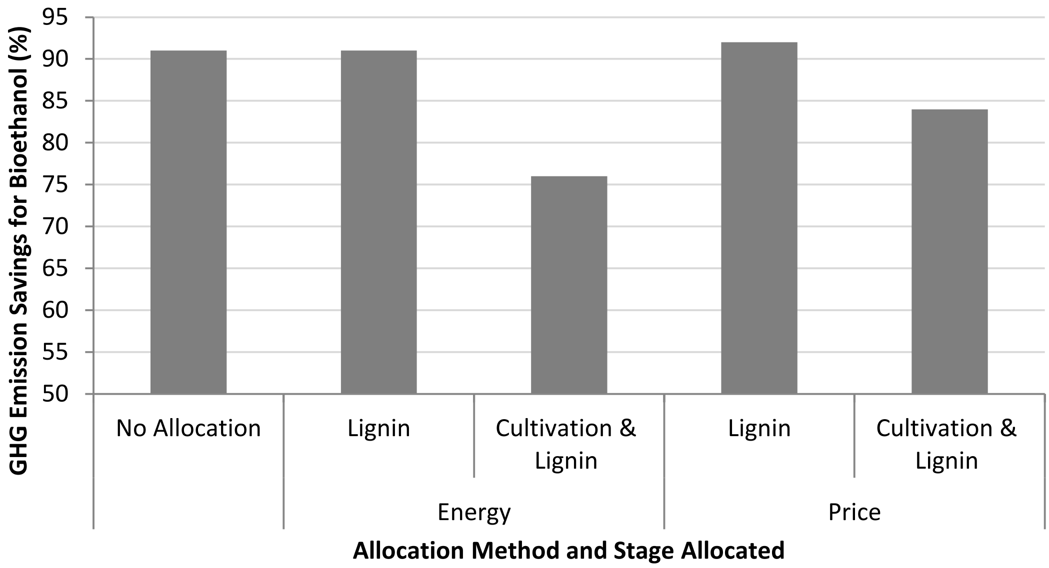

Figure 2 Impact of allocation of cultivation and lignin to bioethanol

4.2. Changes in soil organic carbon

Various studies have examined changes in SOC due to specific LUC events (e.g. Clair et al. (2008) and Hillier et al. (2009)), however changes in residue management, are not as clear cut as conversion of forestland or grassland to arable land (Powlson et al. 2008). Estimates in literature for changes in SOC due to straw management are based on various time-scales and soil types (Table 2) and hence show considerable range. Two resources estimate a loss of 0.39 and 2.35 t $CO_{2\ eq.}$/ha due to straw removal. The references do not state whether can be achieved alongside minimum or conventional tillage. The other resources focus on straw incorporation, with some estimates from process-based models: Powlson et al. (2008) used RothC calculated a sequestration rate of 1.69 t $CO_{2\ eq.}$/ha/year after 20 years of continuous straw incorporation under arable cropping. After this the rate drops to a quarter of this value, leaving an average sequestration rate of 0.77 t $CO_{2\ eq.}$/ha/year. Gabrielle & Gagnaire (2008) estimated that straw removal caused an average increase in emissions of 1 t CO_2/ha in one year, and a sequestration rate of 0.18 to 0.37 t $CO_{2\ eq.}$ per tonne of straw incorporated over a 30 year simulation period. Smith et al. (2005) compared experimental data with that predicted by four commonly used process-based models and found that the majority of SOC losses are less than 4% over 10 years. Assuming a typical carbon content of 53 tC/ha (Reijnders 2008) this would mean that the majority of

SOC losses are less than 0.48 t $CO_{2\ eq.}$/ha/year which corresponds to a SOC change of up to 0.48 t $CO_{2\ eq.}$/ha/year (Smith et al. 2012).

Table 2 Literature estimates of SOC changes due to straw removal or incorporation.

Reference	Carbon Change (t $CO_{2\ eq.}$/ha/year)	Timescale Applicable (years)
Sequestration due to incorporation		
Powlson et al. 2008	1.69	up to 20
Gabrielle & Gagnaire 2008(low)	0.78	30
Gabrielle & Gagnaire 2008 (average)	0.99	30
Gabrielle & Gagnaire 2008 (high)	1.28	30
Hillier et al. 2009	0.58	Not stated
Cherubini & Ulgiati 2010 (IPCC estimate)	2.24	20
Bhogal et al. 2007 (low)	0.55	up to 20
Bhogal et al. 2007 (average)	1.38	up to 20
Bhogal et al. 2007 (high)	2.20	up to 20
Range	**1.11**	
Average	**1.26**	
Min	**0.58**	
Max	**2.24**	
Losses due to residue removal		
Smith et al. 2012, (low)	0.39	10
Smith et al. 2012, (high)	0.78	10
Gabrielle & Gagnaire 2008	2.35	1
Range	**1.96**	
Average	**1.17**	
Min	**0.39**	
Max	**2.35**	

4.3. GHG Implications of nutrient substitution

A summary of various estimates of fertiliser requirements for nutrient substitution is presented in Table 3, and is a continuation of the study published by Whittaker et al. (2011), which calculated that this penalty can decrease the GHG savings of lignocellulosic bioethanol by 1-44. Some references provide estimates for the nitrogen off-take in wheat, whereas some only include P_2O_5 and K_2O, and some only K_2O. Therefore there is uncertainty in both the quantity and type of nutrients required to compensate for straw removal.

Table 3 Literature estimates for the additional fertiliser requirements after straw removal.

Resource	Nutrient Content (kg nutrient/ts)			Fertilizer Penalty (kg $CO_{2eq.}$/tsr)		
	N	P_2O_5	K_2O	N	P_2O_5 & K_2O	N,P_2O_5 & K_2O
Punter et al. 2004	19.4	3.4	33.7	311.2	22.1	333.4
Cherubini & Ulgiati 2010	3.0[a]	2.8	2.2	84.1	6.6	90.7
Plant Nutrient Content Database (n.d.)	7.6	0.8	14.7	122.3	8.2	130.5
Crop Observation and Recommendation Network (n.d.)	5.0	1.4	9.1	80.1	6.9	87.0
Tarkalson et al. 2009	7.4	1.1	9.4	118.0	6.4	124.4
Hollinger n.d.	5.5	1.7	13.6	87.4	9.6	96.9
Copeland & Turley 2008	5.0	1.3	9.3	80.1	6.8	86.9
Potash Development Association (n.d.)	-	1.2	9.5	0.0	6.7	6.7
Withers 1991		1.4	9.3	0.0	6.9	6.9
Brander et al. 2009b[b]	-	-	-	33.3	4.3	37.6
HGCA 2009	-	1.2	9.5	0.0	6.7	6.7
Agro Business Consultants Ltd 2011 (low)	-	-	16.0	0.0	7.2	7.2
Agro Business Consultants Ltd 2011(high)	-	-	7.3	0.0	3.1	3.1
Gabrielle & Gagnaire 2008	-	-	-	48.1	0.0	48.1
Slade et al. 2009[b]	-	-	-	-	-	133.2
Average[c]	9.0	1.8	11.9	**68.9**	**7.3**	**80.0**
Minimum	0.0	0.8	2.3	**0.0**	**0.0**	**3.1**
Maximum	20.0	4.0	33.7	**320.4**	**22.1**	**342.0**

[a] Value is mid-point between low and high estimate.

[b] Resource provided only emission estimates for the fertiliser requirements

[c] Average does not include zeros

The GHG implications for fertiliser manufacture are based on emission factors in the Ecoinvent Database (EcoInvent 2007, ReCipe Midpoint, IPCC100a). Manufacture emissions are given an uncertainty range of +/- 20% with a uniform distribution (Ahlgren et al. 2012). A Monte Carlo Analysis is performed to deduce the range, minimum and maximum results for fertiliser manufacture and N_2O emissions from soil, combined (Table 4). Ammonium nitrate has the highest average emission factor per kg nutrient. This is mainly due to high N_2O emissions from manufacture (EFMA 2000) and soil.

Table 4 GHG emission factors for fertilisers assumed in this study.

	Emission Factor for Fertilisers (kg $CO_{2\,eq.}$/kg nutrient)

Fertiliser	Nutrient	Average	Lower CI	Upper CI	S.D	Min	Max
Ammonium Nitrate	**N**	15.7	15.5	15.8	4.1	7.3	24.2
Triple superphosphate	**P_2O_5**	2.0	2.0	2.0	0.2	1.7	2.4
Potassium chloride	**K_2O**	0.5	0.4	0.5	0.1	0.4	0.5

4.4. Nitrous oxide emissions from crop residues

Table 5 shows the estimated N_2O emissions after performing a Monte Carlo Simulation. Assuming the parameter given in Table 1, the removal of straw from a field leads to the avoidance of 288.6 kg CO2 eq./ha. A sensitivity analysis (not shown) indicates that the results are most sensitive to the grain yield grain (which infers the yield of straw) and the emission factor for N_2O-N/kg N applied.

Table 5 Net GHG balance of straw removal vs. straw incorporation according to results from a Monte Carlo analysis.

Calculation Method	Nitrous Oxide Emissions (kg $CO_{2\ eq.}$/ha)				
	Average Result	**Min**	**Max**	**Lower CI**	**Upper CI**
66% Straw Removal	392.5	98.6	1460.8	659.9	701.8
100% Straw Incorporation	680.8	52.6	915.7	380.0	405.0
Difference	***-288.6***	***-45.9***	***-560.3***	***-279.6***	***-297.1***

4.5. Other Impacts

The diesel fuel consumption for straw baling and harvesting is estimated after reviewing both published resources and farmers guides (Table 6). Where the fuel consumption is estimated it is based on an equation provided by Matthews et al. (1994), and assumes a tractor horsepower of 200, and PTO of 0.85 for harvesting. It is assumed that a 20% fuel increase is required for straw chopping (Glithero et al. 2012).

Table 6 Estimates for fuel consumption rates of baling and straw chopping.

Resource	Fuel Consumption (Litre/ts)	GHG Emission (Kg $CO_{2\ eq.}$/ts)
Baling		
Nemecek	8.6	23.1
Pers. Com. Contractor	3.5	9.3
Lal, 2004	0.6	1.6
Lal, 2004	1.2	3.2
Lal, 2004	1.8	4.9
Williams et al., 2006	1.7	4.6
Bullard and Metcalf	7.7	20.7

BEAT	8.8	23.6
Nix, 2012*	3.1	8.2
Average	**4.1**	**11.0**
Min	**0.6**	**1.6**
Max	**8.8**	**23.6**
Straw Chopping		
Williams et al., 2006	1.1	10.5
Nemecek	1.9	17.9
Nix, 2012*	1.0	10.0
ABC, 2011*	1.6	14.9
Average	***1.4***	***13.2***
Min	***1.0***	***9.6***
Max	***1.9***	***17.9***

* Estimated

4.6. Combined impacts and GHG savings from lignocellulosic ethanol

When the direct GHG implications of straw removal from soil are placed in context with the emissions from straw-based bioethanol production, a GHG saving of between -25% and 90% is achieved. If the avoided or lost emissions from straw incorporation are included an emission saving of between -85% and 125% is found. The direct impacts of straw removal have a smaller overall range of emissions compared to the reference system approach. This is due to high uncertainties in amount of SOC that could have been sequestered if straw was incorporated. Figure 3 demonstrates the impact that minimum and maximum straw removal penalties have on the emissions per GJ bioethanol produced, with 35%, 50% and 60% GHG saving limits shown (compared to gasoline). They show that current estimates of lignocellulosic bioethanol from wheat straw currently fulfil GHG emission targets of over 60%. This is without including any GHG implications of using straw, of which there is great deal of uncertainty. Based on the estimates from literature, the GHG savings of lignocellulosic ethanol may be severely compromised due to emissions occurring due to straw removal. According to the conversion data used in this paper, the threshold for any potential straw removal GHG penalty is 314, 230 and 174 kg $CO_{2\ eq.}$/tsr to reach 35%, 50% and 60% GHG savings.

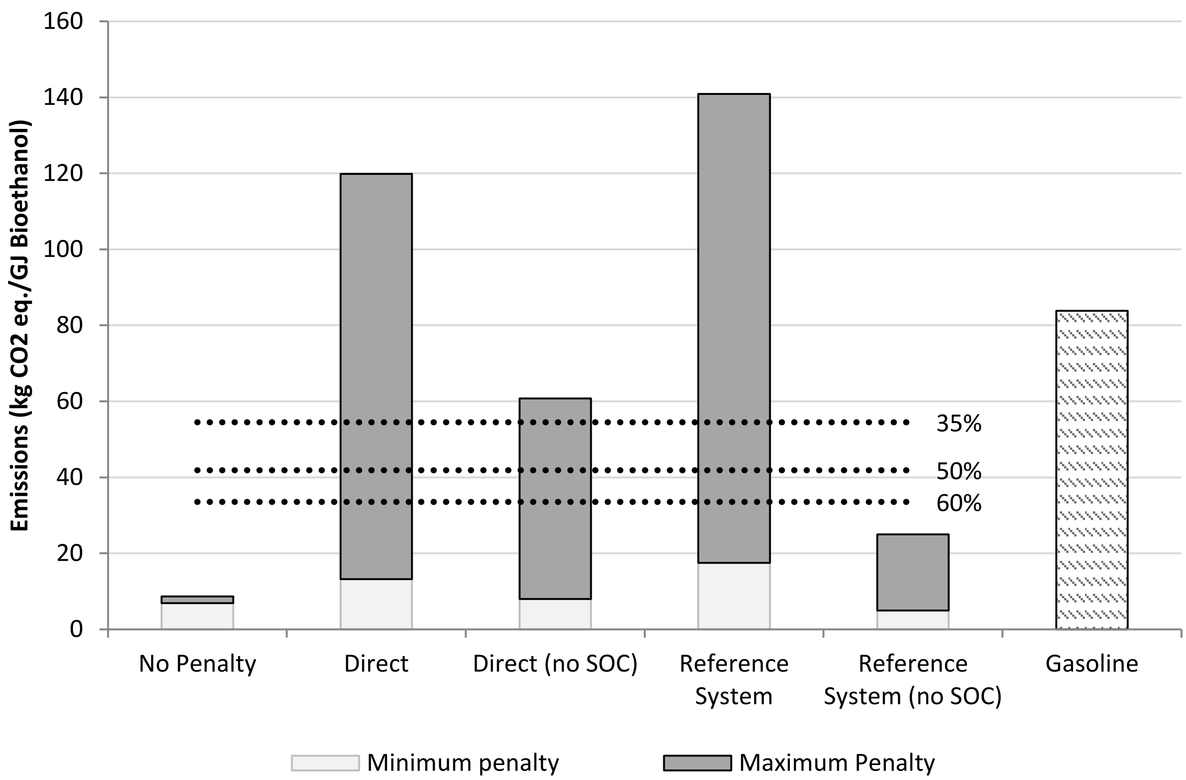

Figure 3 Results of combined GHG impacts of the straw removal penalty including and excluding SOC.

4.7. Sensitivity Analysis

The sensitivity analysis (Figure 4) shows the sensitivity of the GHG emissions of straw-based bioethanol production to the direct and reference system emissions from straw removal. The results are most sensitive to assumptions made on direct changes in SOC due to straw removal. After this, the results are most influenced in the lost benefits of SOC sequestration if the straw was otherwise incorporated. The results are also sensitive to nutrient substitution, mainly due to high emissions from N-based fertilisers. Sensitivities to N_2O emissions from soil and diesel are relatively small.

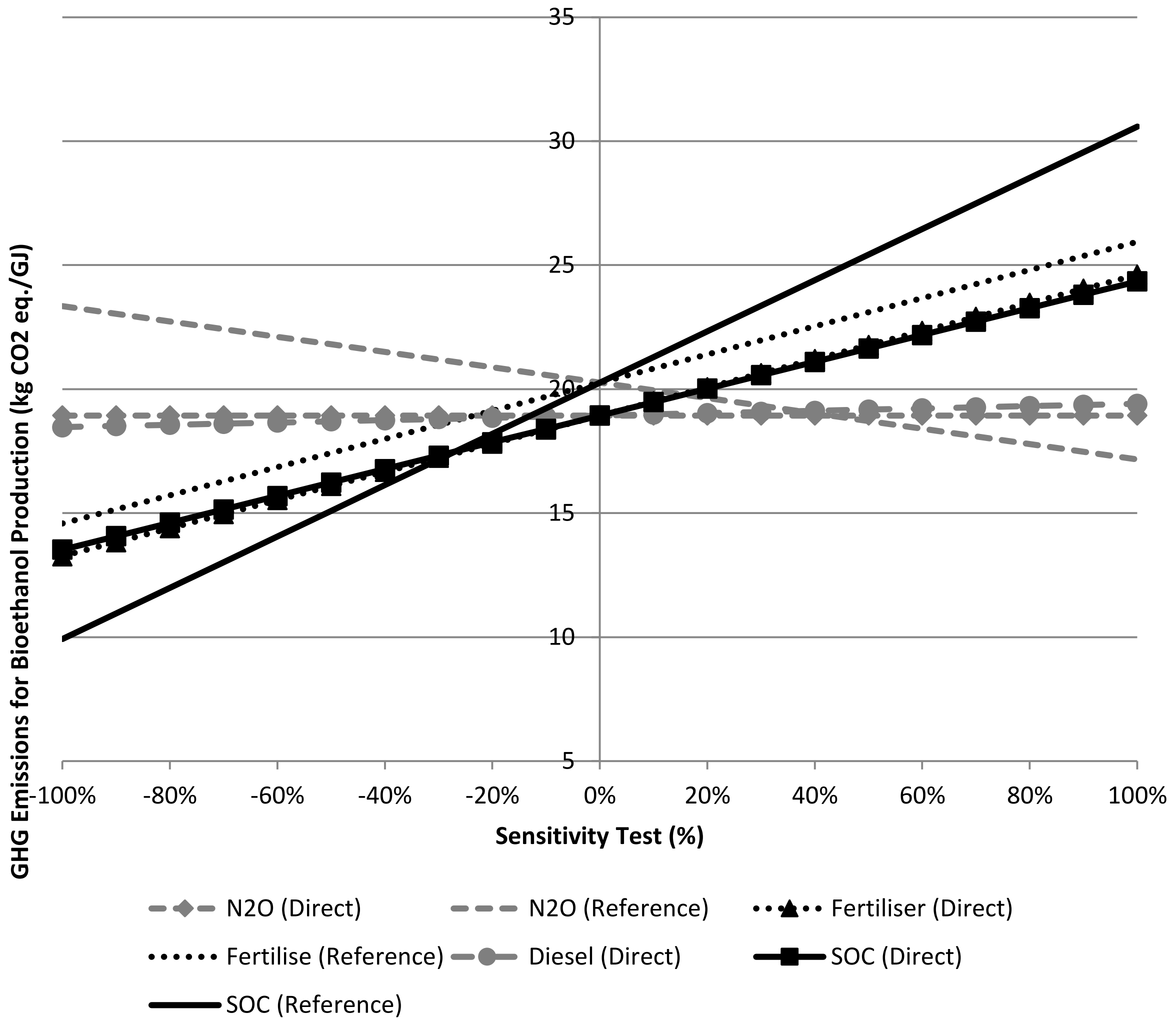

Figure 4 Sensitivity analysis for the contributing parameters to the GHG impacts of straw removal.

4.8. Uncertainty Analysis

The average direct GHG penalty of straw removal is 324.8 kg $CO_{2\ eq.}$/tsr (320-330 kg CO_2 $_{eq.}$/tsr, 95% CI). The main contributors are SOC losses and the direct replacement of lost nutrients by artificial fertilisers. The net balance of emissions between straw removal and straw incorporation, leaves a net positive penalty of 395.9 kg $CO_{2\ eq.}$/tsr (Table 7). The results suggest that straw removal leads to a net higher than if straw was incorporated into the soil to both incorporate SOC and return nutrients to the soil. There is a high degree of uncertainty in both of these effects.

Table 7 GHG implications of straw removal according to results from the Monte Carlo analysis.

	GHG emissions per tonne of straw removed (kg CO2/tsr)			
	Average Impact	CI (lower)	CI (Upper)	Standard deviation
Direct Impacts				
N_2O Emissions	**0.0**	0.0	0.0	0.0

Nutrient substitution	**150.7**	148.5	153.0	36.4
Baling	**12.7**	12.3	13.1	6.3
SOC	**161.4**	156.7	166.1	75.7
Total	**324.8**	319.6	330.0	84.3
Reference System Impacts				
N_2O Emissions	**82.47**	79.6	85.3	45.81
Nutrient substitution	**0**	0.0	0.0	0
Chopping	**13.79**	13.6	13.9	2.43
SOC	**-167.38**	-171.7	-163.0	70.58
Total	**-71.1**	-78.5	-63.7	118.8
Balance: Direct-Reference	**395.9**	395.9	395.9	-0.4

Figure 5 provides a graphical display of the results of the Monte Carlo Analysis for 1 GJ bioethanol produced from wheat straw. According to the analysis, there is a 2% probability that the direct straw penalty will lead to a GHG balance for bioethanol that is greater than gasoline. Due to a greater range of uncertainty, there is an 18% probability that the penalty from lost sequestration will attribute bioethanol with a higher GHG emission than gasoline. Due to lack of data on the probably distribution of each GHG implication of straw removal, the uncertainty analysis must assume that there is a uniform distribution between minimum and maximum straw penalties, and so these results are dependent on this assumption.

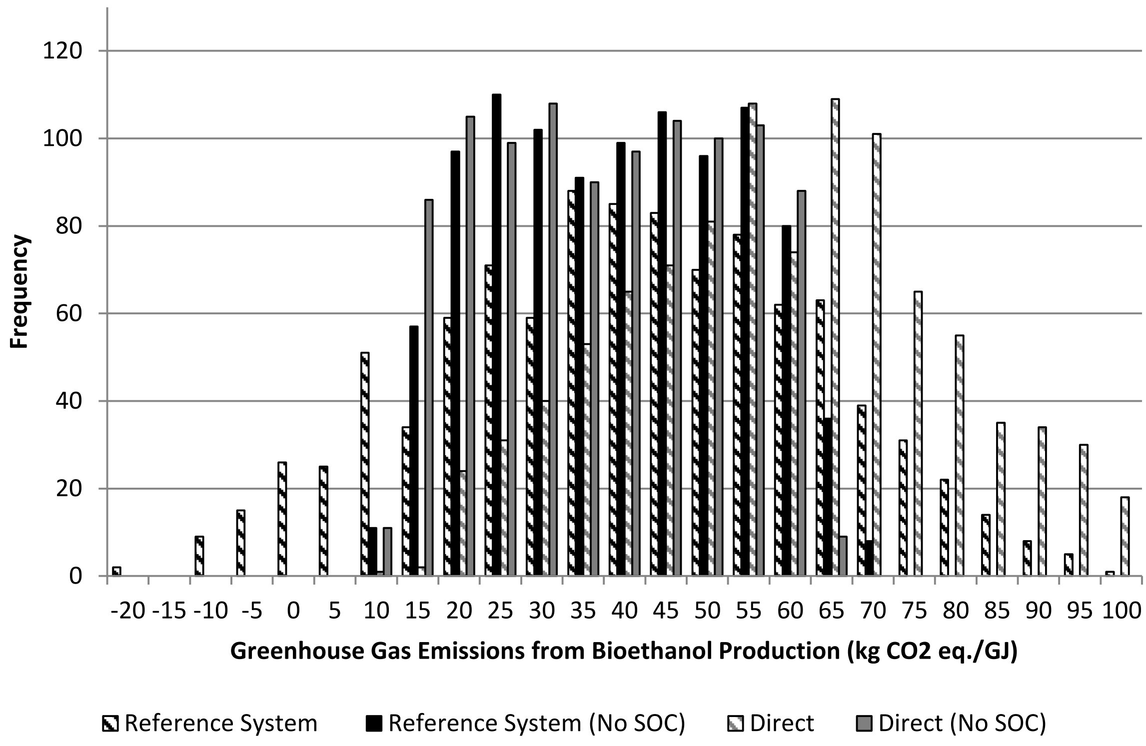

Figure 5 Frequency of results of the GHG intensity of bioethanol production from wheat straw including the straw removal penalty.

5. Discussion

5.1. GHG savings from straw-based bioethanol

The results indicate that wheat straw-based bioethanol has the potential to reach GHG savings of 90-92%. This is higher than the 85% default value presented in the RED. It is possible that similar GHG savings could be achieved when producing bioethanol from other residues, such as from forestry, or waste wood or paper, so long as upstream emissions are not allocated to them. The results suggest that lignocellulosic bioethanol from residues can reach RED targets up to and beyond 2018 with and without allocation. The model estimated that there is a 2% and 18% probability that the direct penalty for straw removal and alternative incorporation scenarios will lead to a GHG balance for bioethanol that is greater than gasoline, respectively. The following sections discuss the relevance of the assumptions made on the GHG implications of straw removal and incorporation.

5.2. The relevance of the straw removal penalties to GHG accounting

There is a high degree of uncertainty in the GHG implications associated with straw removal from soil. A sensitivity analysis indicates that the emissions from bioethanol production are most influenced by assumptions made on the changes in SOC and nutrient substitution.

5.2.1. Changes in SOC

The results are highly sensitive to direct changes of SOC due to straw removal and also by assumptions made on the lost benefits from SOC sequestration in an alternative straw incorporation option. Though there is large variation in the results of the literature review, a consensus is found that SOC decreases with straw removal, and increases with incorporation. The uncertainty analysis assumes a uniform distribution with equal probabilities that the actual impact lay between minimum and maximum changes, though there is a lack of data on the likelihood of SOC change due with different straw management. Excluding the penalty, straw-based bioethanol achieves an average emission saving of 91% compared to combustion of 1 GJ gasoline. The average direct SOC losses due to removal are 161.4 kg CO2 eq./tsr (Table 7) and this decreases the average emission savings to 33%. It is suggested that the majority of SOC changes due to straw removal are in fact less than 4%, or less than 0.48 t $CO_{2\ eq.}$/ha/year (P. Smith et al. 2007), which gives an average emission saving of 82% for straw-based bioethanol.

The uncertainty analysis shows that if straw was incorporated every year, then an estimated 8 to 58 kg $CO_{2\ eq.}$ could be sequestered per GJ bioethanol. Displacement of fossil fuels would lead to the mitigation of 35.6 tonnes $CO_{2\ eq.}$/ha, whereas incorporation could potentially sequester between 3.6 and 26.5 tonnes $CO_{2\ eq.}$/ha. In this case, it appears that the benefits of removing crop residues for bioenergy production outweigh the benefits of incorporation (Cherubini 2010). There is still some uncertainty to the relevance that any change in SOC will have on general soil health. Increases of SOC are reversible, yet losses and subsequent soil damage may be less so, therefore degradation of arable land is a threat to the sustainability of agricultural systems. Soil erosion or degradation may lead to adverse environmental and social impacts when areas of high biodiversity or carbon stock are converted to compensate for this loss of arable land (Edwards et al. 2010). Further research is required to examine how straw removal affects soil fertility, and how to identify susceptible soils.

It has been questioned whether the addition of biological material to soils represents genuine additional carbon storage (Bhogal et al. 2007), suggesting that the 'reference system' approach is not suitable for policy analysis. The RED methodology accounts for direct changes in SOC on a 20 year basis, based on the methodology presented in the IPCC (Bickel et al. 2006). This must therefore account for all losses and gains due to straw management that take place during this time. It is uncertain to how much the SOC sequestration estimates depend on management, however when practicing minimum tillage it is common for ploughing to take place every 3-4 years to alleviate weed, disease and compaction problems, which would reverse any SOC sequestration benefits (Kindred et al. 2008). Process-based models, such as Roth C (Coleman & Jenkinson 2008), or the C-Tool Model (Petersen et al. 2002), can be used to accounting for the GHG implications of straw removal for a single year. In practice however, such modelling relies on a great deal of site-specific data such as soil type, texture, climate and level and frequency of tillage operations (Gabrielle & Gagnaire 2008), leading to more time-consuming accounting. It is otherwise difficult to attribute changes in SOC to a single crop, as it is likely that farmers will follow a rotation of crops and not grow cereal crops continuously. This also ignores other existing markets for straw, and during the 20 year period not all changes in SOC may be attributable to biofuels.

5.2.2. Nutrient substitution

Replacing nutrients that are removed in straw is a relatively new concept in the UK, as straw burning was permitted before 1993. This facilitates the recycling of base nutrients to the soil while serving as a straw management option. After being banned due to environmental concerns (MAFF 1993), farmers must now either incorporate or bale their straw. Nutrient loss is assumed to be a direct impact of straw removal, however the estimates for this range in both quantity and type of nutrient. Estimates that include nitrogen have a significantly higher GHG penalty than those only including phosphorous and potassium, as this is more GHG intensive to manufacture due to high energy demands for ammonia production and significant N_2O emissions from nitric acid production and reaction with ammonia (EFMA 2000). It is therefore important to determine whether there are any increases in nitrogen requirements in the following crop due to straw removal. Most estimates in Table 3 do not attribute a nitrogen content to straw, assuming that this is removed in the grain component as protein (Whitbread et al. 2003). It is suggested that N requirements increase if straw is incorporated, due to immobilisation of N during straw decomposition (Limon-Ortega et al.

2008), therefore it is inappropriate to include N substitution (Kindred et al. 2008). Databases listing the nutrient content of straw suggest that it is responsible for K recycling, rather than P or N (Agro Business Consultants Ltd 2011; PDA n.d.; Withers 1991).

The high nutrient substitution rate given by Punter et al., 2004, is criticised that this does not reflect current practice, and that fertiliser applications will be made independent of residue management (Kindred et al. 2008). The one reference that may influence current practice in the UK is the Agricultural Budgeting and Costing Book (Agro Business Consultants Ltd 2011), which specifies that an additional potassium of 40 kg/ha is required if straw is removed from a wheat crop. Based on a straw yield of 2.5 to 5 tonnes/ha, this corresponds to a nutrient content of 7.3 to 16 kg K_2O/ts. The majority of the estimates in literature fall within this range. Therefore, there is evidence that the GHG penalty is only attributed with potassium recycling, and this has a small impact on the emissions savings of lignocellulosic bioethanol.

It must be noted that the fertiliser substitution penalty is necessary to avoid decreases in grain yield due to straw removal. Decreases in grain yield may not directly affect the GHG balance of a given tonne of straw, yet yield losses will place pressure on agricultural land to replace the grain that is no longer being produced, leading to adverse environmental and social impacts when areas of high biodiversity or carbon stock are converted for arable use (Edwards et al. 2010; Nuffield Council on Bioethics 2011). This is something that must be avoided in order for biofuels to be sustainable, and this is important to understand both in terms of practical management of arable crops, and in GHG reporting.

5.2.3. Summary of relevant GHG implications of straw removal

After further analysis of the relevant aspects of straw removal, the direct GHG implications of removal of straw are estimated to be small. A direct penalty of a 4% loss of SOC, and potassium off-take in straw, the GHG emission saving of wheat straw-based bioethanol is 79-84%. Assuming a minimum SOC sequestration rate gives GHG savings of 60 to 79% in the reference case scenario, however this impact is not considered to be relevant to biofuel reporting. These results comply with RED targets for beyond 2018, suggesting that the GHG implications of straw removal do not compromise the GHG savings lignocellulosic bioethanol (Figure 6). There are some uncertainties in this. The need to understand changes in SOC and the nitrogen off-take in straw has been identified.

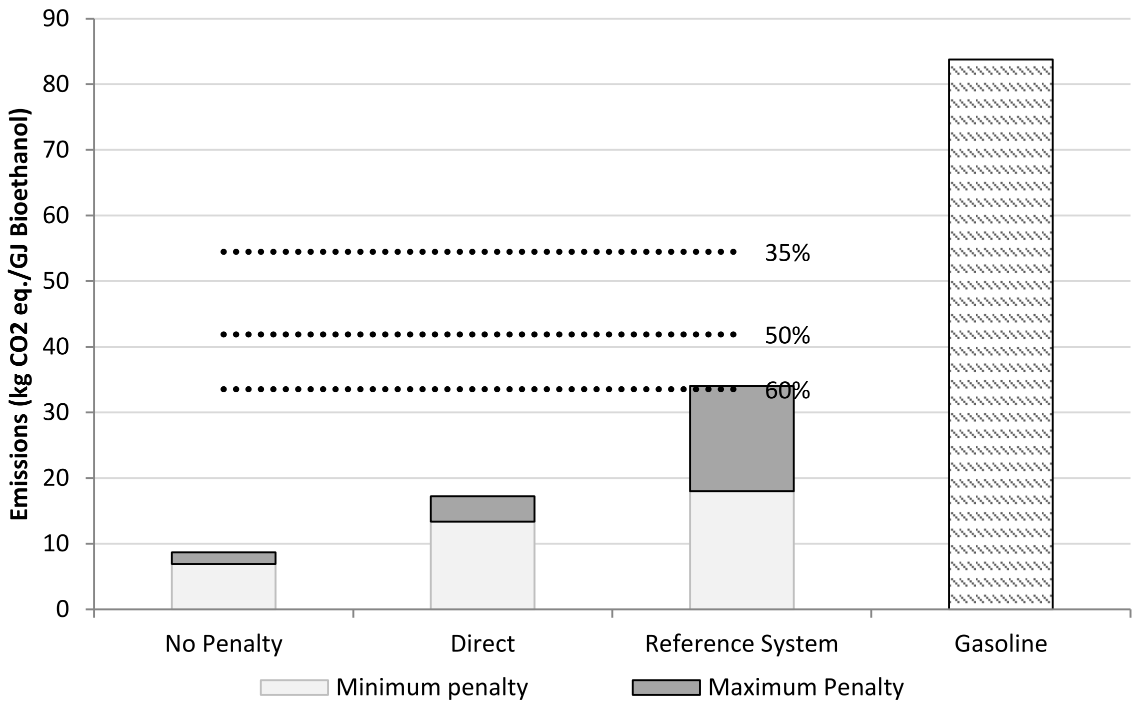

Figure 6 GHG emissions from bioethanol production from wheat straw including the minimum GHG penalty for straw removal.

5.3. Issues with the accounting methodology

The direct impact of straw removal and the reference system of foregone sequestration or avoided emissions from straw incorporation represent two approaches to accounting for GHG implications of using straw. Both examine the issue in a different manner, and provide a separate account of what occurs when straw is removed from soil.

Direct impacts are directly the cause of the farmer or biofuel producers' actions. These impacts should be accounted for in GHG reporting. They are associated with ALCA (Brander et al. 2009a), which is considered appropriate for accounting and regulation of GHG. This study has demonstrated that ALCA impacts of straw removal compromise the GHG emission saving potential of lignocellulosic bioethanol to some extent.

A 'reference system' is not required for an LCA to comply with the ISO standards. It represents a notional scenario for what would have happened if biofuels were not produced (Bird et al. 2011; Kindred et al. 2008). There can be uncertainty in deciding on the most appropriate reference system, and decisions on this can have major consequences on the GHG impacts of a biofuel (Kindred et al. 2008). There is also uncertainty in the level of

responsibility that a farmer has over the alternative scenario if biofuels were not produced. A farmer can decide whether to incorporate or remove their straw, but may respond to market forces when doing so. There are other existing markets for straw (Brander et al. 2009b). Consequential LCA (CLCA) is used to provide information on the net change of environmental impacts due to change in production of a product (Sanchez et al. 2012). The difference between a 'reference system' and a 'consequential impact' is that the former accounts for an alternate fate of a material, whereas the latter examines how materials are substituted. The reference system approach in this study assumes that the additional supply of straw required to contribute towards the EU's 10% renewable energy target will be acquired from increased removals from soil. This study has not examined the impacts of replacing existing uses of straw, of which there is also great deal of uncertainty.
Brander et al. (2009b), suggests that Miscanthus can be used to replace straw as animal bedding, however the production of Miscanthus involves the use of land which increases the complexity of the assessment (Kindred et al. 2008). Therefore, the full consequential GHG implications of utilising straw will depend on where it is being sourced from, either from increased removals from soil, or from existing supply.

5.4. Sustainable removal

As straw is a limited resource, it is important that it is used efficiently and effectively (Kindred et al. 2008). It is important that GHG reporting does not distort practices that may lead to a compromise in soil fertility and function (Bhogal et al. 2007). A certain reliance on farmer-expert knowledge is required for them to follow residue management methods to best comply with the EU Common Agricultural Policy. It is also the case that straw retention can lead to problems with pests (HGCA 2009), emergence of seedlings (Morris et al. 2009) and nitrogen immobilisation (Limon-Ortega et al. 2008), therefore GHG reporting should not penalise against straw removal for avoidance of these issues. In some cases, residue retention limits must be identified for individual sites in order for soil amendment to be achieved alongside providing a renewable source of fuel without competing directly with food crops. It is suggested, however, that even small removal rates of 20-40% can cause losses in SOC, which have been demonstrated to significantly compromise the GHG saving potential of lignocellulosic biofuels (Reijnders 2008). Residue removal limitations may also mean that less straw is available per unit area, becoming a more widely dispersed and hence less economically favourable resource. A key issue is determining the likelihood that bad practice that causes soil damage is adopted, as this will indicate whether GHG reporting should include impacts of straw removal. There is evidence that current practices have caused losses in SOC of between 4% and 23% in the UK due to increased cultivation intensity (King et al. 2005), and there is currently predicted that agricultural production will become more intensive in the near future (Mondini & Sequi 2008). Residue management may therefore become more important for the long-term sustainability of agriculture; therefore it should be regarded as an important issue in the sustainability of biofuels.

6. Conclusion

Lignocellulosic biofuels are expected to contribute to 5% of total UK energy consumption by 2020 (ICCT 2012). Strict emission saving targets of 60% are demanded for installations that start after January 2017 (EC 2009), or after January 2014 under current proposals to revise the RED targets (ICCT 2012). The RED promotes the use of cereal residues as a feedstock for bioethanol production, however there are large uncertainties in the GHG implications of straw removal, particularly regarding changes in SOC and nutrient off-take. It is estimated that GHG savings of 90-92% can be achieved from production lignocellulosic bioethanol from wheat straw. The direct GHG implications of removing straw are estimated to reduce these savings to -43 to 84%. After further review, it is suggested that straw incorporation is not implicated in nitrogen recycling, and that the majority of SOC changes are small. In this case the GHG savings of bioethanol from wheat straw are in the region of 79-84%. This suggests that accounting for straw removal does not compromise the ability for lignocellulosic bioethanol to reach GHG saving targets set by the RED between now and after 2018.

If the alternative option of managing straw was to incorporate it into the soil then this could sequester between 3.6 and 26.5 tonnes $CO_{2\ eq.}$/ha, where substitution of fossil fuels would avoid 35.6 tonnes $CO_{2\ eq.}$/ha. It is questionable whether such ‘foregone’ sequestration can be considered in GHG assessments of biofuel policy as the magnitude of sequestration of SOC is uncertain, and reversible, whereas fossil substitution is not. Therefore wheat straw can play a major role in GHG mitigation in the transport sector, however there is a clear need to understand the full limitations of residue removal from soil to ensure that it used sustainably.

The results demonstrate that allocation can have as large an impact on the results as the uncertainty of GHG implications of straw removal. Though the RFA identifies straw as a by-product, it has an obvious role in maintaining SOC and is a relatively valuable product of cereal farming. Allocation by price may reflect this relative value, and it can be argued that allocating emissions to straw will provide evidence to whether this biomass resource returns truly favourable GHG savings. Allocating emissions to a co-product does not automatically imply its sustainability is being accounted for. The main risk of this aspect of the RED methodology is not the lack of allocation of emissions to straw, but the lack of acknowledgement of the role of residues in soil. Understanding this is important to understand any direct damage that straw removal poses, but also the potential consequences of the RED renewables policy.

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