An insights report by the
Energy Technologies Institute

Bioenergy
Delivering greenhouse gas emission savings through UK bioenergy value chains

Contents

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Key headlines

» From a long term low carbon perspective Bioenergy with Carbon Capture and Storage (CCS) is a game-changer, since most of these value chains, when using certain UK-grown bioenergy crops, would deliver substantial negative emissions

» Bioenergy offers flexibility to a future UK energy system – it can be deployed to meet around 10% of future energy demand and deliver net negative CO_2 emissions of *c.*-55million tonnes per year in the 2050s

» Numerous bioenergy value chains can deliver genuine system-level carbon savings, across all key vectors of power, heat, liquid and gaseous fuels

» If bioenergy is deployed without CCS, greenhouse gas (GHG) emission savings are still achievable given the right choice of crop type, location, and end use in the energy system

» Sustainability, security of supply and public acceptability can be increased if the UK doesn't rely entirely on biomass imports, and instead uses a mixture of 'home-grown' and imported feedstock

» Planting 30,000 hectares a year of second generation bioenergy crops on marginal arable land or appropriate grassland would keep us on the trajectory for scaling up domestic biomass production out to the 2050s

» Taking these decisions and actions over the next 5-10 years protects the UK's option to pursue the lowest cost route to delivering our climate change commitments by 2050

Executive summary

Bioenergy can play a significant and valuable role in the future UK energy system, especially when combined with CCS. Together they can deliver net negative emissions of c.-55 million tonnes per year, and meet around 10% of UK energy demand in the 2050s, ultimately reducing the cost of meeting the UK's 2050 GHG emission reduction targets by more than 1% of GDP[1]. Yet the bioenergy sector is immature, reflecting both its complexity, in terms of the multiple value chains that could be deployed; and the political and scientific uncertainties around land use change and the sustainability of using biomass for energy. The UK Government has highlighted the need to ensure that bioenergy delivers genuine carbon savings, and that the impact of direct land use change (dLUC) to biomass production is better understood. The work presented here addresses these issues for bioenergy crops in the UK, and has enabled the ETI to identify options for delivering GHG emission savings through UK bioenergy value chains.

» Carbon Capture and Storage is a game-changer. Bioenergy value chains with CCS render dLUC emissions of second-order importance, since virtually all CCS value chains using second generation (2G) bioenergy crops[2] grown in the UK would deliver substantial negative emissions to the UK. This work strengthens the link between biomass and CCS, which remains the only credible route to deliver genuine negative carbon emissions at the scale necessary to meet the UK's 2050 GHG emission reduction targets[3]

» Bioenergy can offer flexibility for low carbon energy supply in a future UK energy system, since numerous bioenergy value chains can deliver genuine system-level carbon savings, across all key vectors of power, heat, liquid and gaseous fuels

» If bioenergy is deployed without CCS, dLUC emissions can be material, either contributing GHG emission savings or producing additional emissions at the value chain level, depending on choice of crop type, location, and ultimate use in the energy system

» Sustainability, security of supply and public acceptability can be increased if the UK doesn't rely entirely on biomass imports, and instead uses a mixture of 'home-grown' and imported feedstock. This requires action and support to expand the UK's nascent biomass production sector, incentivising the production of sustainable feedstock in ways that fit with current farming and land management systems, ultimately maximising land use and value chain productivity

» Planting 30,000 hectares a year of 2G bioenergy crops, over the next decade would keep us on the trajectory for scaling up domestic biomass production out to the 2050s. This planting would ideally be on marginal arable land, or grassland in appropriate locations. A ramp-up of this scale is comparable to existing arable cropping land use changes, and would enable the benefits of integrating biomass production alongside food production to be demonstrated

» Taking these decisions and actions over the next 5-10 years protects the UK's option to pursue the lowest cost route to delivering it's climate change commitments by 2050. It also provides time to develop a framework to optimise the efficiency, economic and environmental performance of the UK agricultural sector as a whole

[1] Based on opportunity costs derived from ESME modelling. http://www.eti.co.uk/project/esme

[2] 2G Bioenergy crops denote ligno-cellulosic feedstocks such as Miscanthus, Short Rotation Coppice Willow (SRC-W) and Short Rotation Forestry (SRF).

[3] Negative emissions of 55 million tCO_2/year are required to meet our 2050 targets, offsetting the need for expensive and difficult interventions in aviation, shipping and transportation sectors. http://www.eti.co.uk/project/esme

Introduction

Bioenergy can help significantly reduce the cost to UK consumers and taxpayers of meeting 2050 GHG emission reduction targets, especially when combined with CCS. The ETI's analysis informed by ESME[4], an internationally peer-reviewed Energy System Modelling Environment, suggests that bioenergy can be deployed to deliver net negative GHG emissions of around -55 million tonnes of CO_2 per year in the 2050s (approximately half our emissions target in 2050), and meet around 10% of UK future energy demand (~130 TWh/yr in 2050). Deployed properly, bioenergy has the potential to help secure energy supplies, mitigate climate change, and create significant green growth opportunities[5]. It is therefore important to understand fully the end-to-end elements across the bioenergy value chain: from crops and land use, to conversion of biomass to useful energy vectors, and the manner in which it is integrated into the rest of the UK energy system (e.g. into transport, heat or electricity).

The ETI has commissioned and funded several projects under its Bioenergy Programme – including the "Ecosystem Land Use Modelling" project (ELUM)[6], and the "Bioenergy Value Chain Modelling" project (BVCM)[7]. When ETI commissioned the ELUM project in 2010, there was little empirical evidence of the impact of land use change to bioenergy crops within the UK. Reports at the time – most notably the Gallagher Review (2008) by the UK Renewable Fuels Agency[8], and Defra's 'Safeguarding our Soils' strategy for England (2009)[9], highlighted an urgent need to better understand the impact that land use change to biomass could have on soil carbon and GHG fluxes. Understanding the effects of land's existing use, land's productive potential, the net carbon impact of using land for biomass, and land's existing environmental value were identified as priorities by them.

[4] http://www.eti.co.uk/project/esme/

[5] Bio-TINA: http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/bioenergy/ and NNFCC: https://www.gov.uk/government/publications/jobs-in-the-bioenergy-sectors-by-2020

[6] The Ecosystem Land Use Modelling & Soil C Flux Trial (ELUM) project has delivered an evidence-based understanding of the impact on soil carbon and greenhouse gas (GHG) flux, of land use changes associated with biomass production in the UK. It adopted a unique approach of 'measuring and modelling' changes to soil carbon and GHG flux, and delivered a comprehensive dataset and modelling tool, enabling the potential direct land use change (dLUC) impacts of biomass production across the UK to be assessed. Information available at: http://www.eti.co.uk/project/ecosystem-land-use-modelling-elum/

[7] The Bioenergy Value Chain Model (BVCM), is a comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains in the UK over the next five decades. Information available at: http://www.eti.co.uk/project/biomass-systems-value-chain-modelling/

[8] Gallagher Review (2008): UK Renewable Fuels Agency review of the indirect effects of biofuels. http://webarchive.nationalarchives.gov.uk/20110407094507/renewablefuelsagency.gov.uk/reportsandpublications/reviewoftheindirecteffectsofbiofuels

[9] Defra (2009) – Safeguarding our Soils: A Strategy for England. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69261/pb13297-soil-strategy-090910.pdf

Introduction

Continued »

Land use change associated with biomass production may affect the soil carbon stocks and GHG emissions of the land planted, including (CO_2), methane (CH_4) and nitrous oxide (N_2O). Under the EU Renewable Energy Directive, "direct land use change (dLUC) emissions" refer to changes in carbon stocks held within the soil and vegetation associated with a change in land use and management practices from a 'prior' land use to the 'new' bioenergy crop production. This is distinct from "indirect land use change (iLUC) emissions" which are the GHG emissions arising from additional land use change elsewhere, when the displaced agricultural activity is continued in an alternative location. "Sustainable intensification" is sometimes used to describe scenarios where no 'alternative' land is required, since productivity is maintained due to agronomic improvements such as enhanced yield or better management practices.

The need for evidence on dLUC emissions, and soil carbon changes specifically, has been re-iterated in more recent publications, including the Committee on Climate Change's Bioenergy Review (2011)[10], and the UK Government's Bioenergy Strategy (2012)[11], which states the importance of "ensuring bioenergy delivers genuine carbon reductions". Bioenergy could generate savings or produce additional emissions at each stage along the value chain, such as during biomass production, or the resultant conversion of that biomass in wider bioenergy value chains. ETI sought to generate an evidence base and assessment tools relevant to these priority areas through both ELUM and BVCM.

The ETI published an insights report in March 2015 which highlighted the learnings from using the BVCM toolkit[12], and the key points are repeated below. This insights report presents the evolution of that work, incorporating data arising from the ELUM project on soil carbon changes to calculate dLUC emissions, and examining a) how material they are in UK bioenergy value chains, and b) identifying which UK value chains offer a significant opportunity to deliver GHG savings relative to fossil baselines.

"Bioenergy can help significantly reduce the cost to UK consumers and taxpayers of meeting 2050 greenhouse gas emission reduction targets."

[10] CCC Bioenergy Review (2011) https://www.theccc.org.uk/publication/bioenergy-review/

[11] UK Government Bioenergy Strategy (2012) https://www.gov.uk/government/publications/uk-bioenergy-strategy

[12] http://www.eti.co.uk/wp-content/uploads/2015/03/Bioenergy-Insights-into-the-future-UK-Bioenergy-Sector-gained-using-the-ETIs-Bioenergy-Value-Chain-Model.pdf

1. BVCM Insights

The ETI's BVCM is a comprehensive and flexible toolkit for the modelling and optimisation of full-system bioenergy value chains in the UK over the next five decades[13]. It has been designed to answer variants of the question: "What is the most effective way of delivering a particular bioenergy outcome in the UK, taking into account the available biomass resources, the geography of the UK, time, technology options and logistics networks?"

Key insights

- Biomass combined with Carbon Capture and Storage remains the only credible route to deliver negative emissions, necessary to meet the UK's 2050 GHG emission reduction targets affordably
- Biomass offers significant system flexibility, since it can be used to generate power, heat, liquid and gaseous transport fuels, and negative emissions; and can be used to meet future base, and peak-energy demands
- Bio-hydrogen and bio-electricity are produced in preference to biofuels and bio-methane, when minimal system GHG emissions is a key driver
- Bio-heat is deployed across the UK, especially in early decades, when it has a key role in stimulating local markets for sustainable biomass feedstocks
- Gasification technology is a key bioenergy enabler, producing both hydrogen and syngas, and is one of the most flexible, scalable and cost-effective bioenergy technologies
- Locational preferences for resource production are apparent: with Short Rotation Coppice Willow (SRC-W) in the west / north-west of the UK, and Miscanthus in the south and east of the UK. Short Rotation Forestry (SRF), when grown, is preferred in the central, south and east of England
- Hubs of bioenergy production with CCS appear to be efficient value chain options: with gasification to hydrogen with CCS in the west of England (at Barrow) and Combined Cycle Gas Turbines (CCGT) running on syngas with CCS in the east of England (at Thames and Easington), based on key 'resource-conversion-CCS' pathway optimisation
- Imports (and port capacity) influence the location of key deployments of CCS technologies
- UK land is finite, valuable and often under-utilised. With the right prioritisation, it could deliver sufficient sustainably-produced biomass feedstock to make a hugely important contribution to the delivery of the UK's overall GHG emission reduction targets

BVCM

Bioenergy Value Chain Model
Optimising Bioenergy

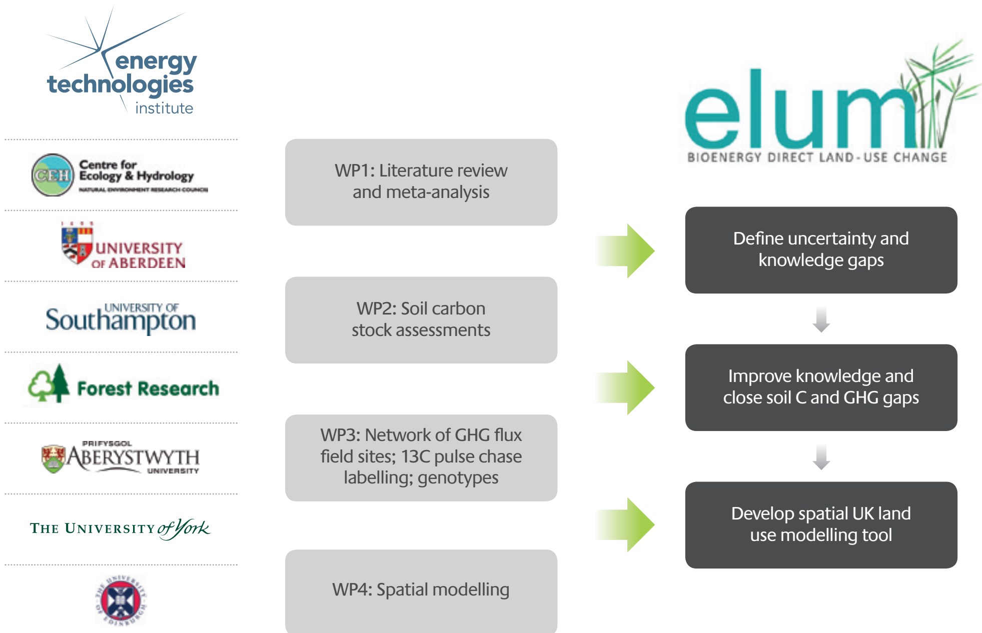
[13] For more detail on BVCM's functionality see: ETI Overview of BVCM http://www.eti.co.uk/wp-content/uploads/2015/03/BVCM-Guide-FINAL.pdf ; and Samsatli, S. et al. (2014) BVCM: a comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – mathematical formulation. Applied Energy, 147, 131-160. http://dx.doi.org/10.1016/j.apenergy.2015.01.078

2. The ELUM project

The ELUM project was commissioned to provide more data and understanding of soil carbon and GHG fluxes arising as a result of land use change to bioenergy feedstocks, with a primary focus on the second-generation bioenergy crops Miscanthus, SRC-W and SRF. Estimation of iLUC was out of scope. The project was delivered by a consortium of seven UK partners: the Centre for Ecology & Hydrology (CEH), University of Aberdeen, University of Southampton, Forest Research, University of Aberystwyth, University of York and University of Edinburgh. The four year, £4m project was led by CEH and consisted of four work packages (see Figure 1). The ETI project was unique in that the majority of fieldwork was conducted on commercial farms across the UK, rather than in controlled plot-scale experiments; and that modelling and fieldwork was brought together under one project.

FIGURE 1

Overview of the ETI's ELUM project



An extensive literature review and meta-analysis highlighted knowledge gaps around the impact of land use change to bioenergy crops on soil carbon and GHG flux. Paired site comparisons of 70 land use transitions at locations across the UK were used to assess the longer-term impact on soil carbon. A network of new sites was established to monitor GHG emissions and soil carbon changes following land use change, representing a world-leading infrastructure from which to assess long-term impacts of land use change. Plot experiments were used to assess mechanisms underpinning soil carbon sequestration in Miscanthus, and the variation between 15 different genotypes representing the current diversity within the UK Miscanthus breeding programme[14]. Fieldwork within the ELUM project focused on measuring changes to soil carbon at depths to one metre, soil GHG fluxes, net ecosystem exchange (NEE), and carbon partitioning to different parts of the system (air, above-ground vegetation, roots, rhizomes and the soil) – see Figure 2.

The project developed a meta-model, designed to assess the potential impact of biomass production across the UK, based on outputs from the well-established ECOSSE soil carbon and GHG model produced by the University of Aberdeen[15] – recognised for being easily developed from a field based model to a national scale tool, without high loss of accuracy[16]. An essential aspect of generating ECOSSE model outputs, and developing the meta-model, was ensuring sufficient and suitable data were available for model parameterisation and validation. The model outputs provided detailed spatial data on the direct effects of land use change to bioenergy crops on soil carbon stocks and soil GHG emissions in the UK.

[14] Harris, Z.M. et al. (2014) The ELUM project: Ecosystem Land Use Modelling and Soil Carbon GHG Flux Trial, Biofuels (2014), 5, 111-116. http://dx.doi.org/10.4155/bfs.13.79

[15] Smith, J.U. et al. (2010) Estimating changes in Scottish soil carbon stocks using ECOSSE – Part 1. Model description and uncertainties. Climate Research, 45, 179-192. http://dx.doi.org/10.3354/cr00899

[16] Robertson, A.D. et. al. (2015) "Modelling the carbon cycle of Miscanthus plantations: existing models and the potential for their improvement". GCB Bioenergy, 7, 405-421. http://dx.doi.org/10.1111/gcbb.12144

2. The ELUM project

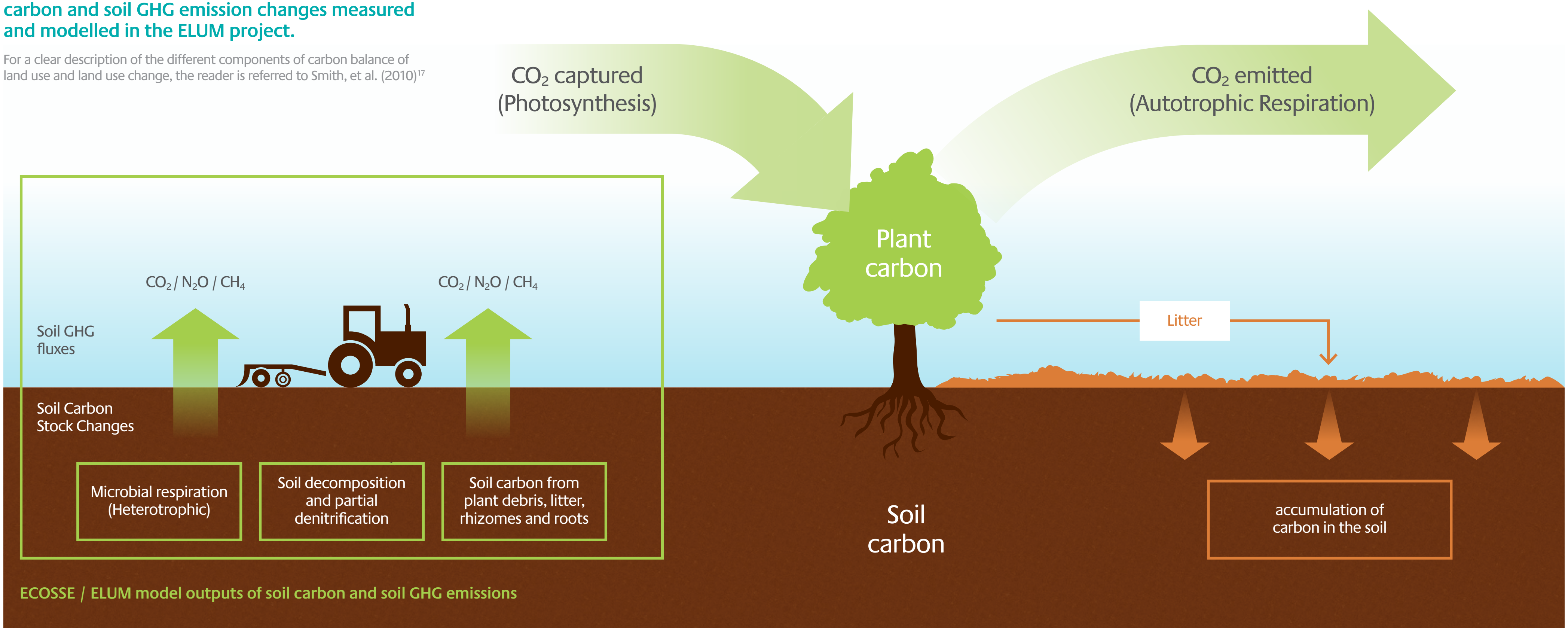
Continued »

FIGURE 2

Schematic representation of components of soil carbon and soil GHG emission changes measured and modelled in the ELUM project.

For a clear description of the different components of carbon balance of land use and land use change, the reader is referred to Smith, et al. (2010)[17]

Note: harvested material was not measured in ELUM specifically



[17] Smith, P. et al. (2010) Measurements necessary for assessing the net ecosystem carbon budget of croplands. Agriculture, Ecosystems and Environment, 139, 302-315 http://dx.doi.org/10.1016/j.agee.2010.04.004

2.1 Summary of key data generated from the ELUM project

Table A1 in the Appendix provides a high-level summary of the key data generated from ELUM, and lists the many individual peer-reviewed academic papers that have been published from the project. General observations on these data are:

- Soil N_2O emissions were seen to be small relative to CO_2 emissions from the soil, and CH_4 emissions were found to be negligible across all transitions to 2G bioenergy crops assessed at ELUM field sites
- Changes in soil carbon stocks were the primary determinant of whether a given transition to bioenergy crops was beneficial or negative in terms of a site's net soil GHG emissions, modelled over 40 years
- Transitions from arable land to 2G bioenergy crops (Miscanthus, SRC-W or SRF) showed net GHG savings (increase in soil carbon and/or reduction in GHG fluxes), relative to continued arable land use. These savings were predominantly seen as gains in soil carbon in the top 0-30cm layer, likely to be due to some combination of: a) less disturbance of soil through tillage / harrowing[18]; b) less fertiliser inputs (resulting in reduced N_2O emissions and negligible CH_4 emissions); and c) less microbial driven losses of soil carbon, so more carbon retained in soil
- Across the UK, the mean net soil GHG emissions for land use changes from arable to 2G bioenergy crops were -84, -42 and -144 tCO_2e per hectare ("/ha"), cumulative over 40 years for Miscanthus, SRC-W and SRF respectively (i.e. all delivered GHG savings). Figure 3 shows the predicted impact over 40 years for all ELUM transitions, relative to continued arable, grassland or forest land use (the counterfactual). This shows that arable to high-yielding SRF transitions offer the greatest GHG savings potential for this part of the value chain. The cumulative emissions impact (over 40 years) in tCO_2e per oven dried tonne is shown in Figure 4, and the impact of lower-yielding crops is illustrated by the relatively higher emissions of oilseed rape

Measuring greenhouse gas fluxes from cultivated land under ETI's ELUM project

[18] Tiemann, L.K. and Grandy, A.S. (2015) highlighted importance of soil management decisions that minimise disturbance and soil aggregate destruction. In: Mechanisms of soil carbon accrual and storage in bioenergy cropping systems. GCB Bioenergy, 7, 161-174. http://dx.doi.org/10.1111/gcbb.12126

2.1 Summary of key data generated from the ELUM project

Continued »

- Soil carbon losses were higher in soils initially rich in soil organic carbon at Miscanthus and SRC-W sites
- The establishment of SRF on UK agricultural land is likely to result in either no change in soil C, or a small increase, depending on the tree species planted. Coniferous SRF species such as Sitka Spruce were seen to have an increase in soil carbon at both 0-30cm and 0-100cm depths relative to control sites, whereas broadleaf SRF species tended to see no change in soil carbon levels (i.e. a neutral transition)
- Transitions from grassland to first generation (1G) crops: wheat, oilseed rape and sugar beet, showed significantly greater net increases in soil GHG emissions than grassland to 2G bioenergy crops, the former being 128, 137 and 146 tCO_2e/ha respectively (see Figures 3 and 4)
- Transitions from forest to any other crop were generally seen to result in increased soil GHG emissions, as a result of reductions in soil carbon and increased CO_2 fluxes. Net GHG emissions of 107, 134 and 92 tCO_2e/ha after 40 years were predicted for Miscanthus, SRC and SRF respectively, compared to leaving it as mature forest[19]
- Modelling outputs showed the spatial distribution of locations likely to deliver net soil GHG savings varied by transition type, as shown in Figure 5. Favourable locations for arable to 2G bioenergy crop transitions were relatively uniformly spread across the UK; whilst locations for grassland to SRF transitions for example, were concentrated in the central to southern parts of the UK
- Yield had a larger impact on modelled net soil GHG emissions than small variations in fertiliser input (+/- 20% around Defra guideline amounts), or climate scenario predictions (UKCP09[20]), with higher yields resulting in lower emission levels over 40 years (see Figure A1 in Appendix)

The yield data used in ECOSSE and the ELUM meta-model did not have agronomic improvements (either management practices or breeding programmes) built in over the 40 years, and hence may be on the conservative side. ETI undertook additional modelling work to examine the effect of more representative yield assumptions on soil GHG emissions, since a realistic and sensible deployment strategy would involve the planting of a diverse range of species and cultivars that were more resistant to diseases, pests and severe weather, than single species or varieties; whilst delivering economic yields. This diversity would ensure a more robust, economic, ecological, productive and sustainable agricultural system, and should be the basis of any national strategy to increasing biomass production in the UK.

[19] In the ELUM modelling, this describes the removal of existing forestry stock and the replacement with alternative bioenergy crops. McKay (2011) indicated that soil carbon losses can be avoided by planting new forestry feedstock 'plugs' (new plants) in between old stumps, in order to minimise ground disturbance, and therefore soil carbon loss. In situations where new forests are created, or existing forests have been under long-term management for production of timber and /or biomass, Matthews et. al. (2014) found harvesting of wood did not incur a 'carbon debt', and that management of UK forests for wood production can contribute to UK carbon objectives. McKay, H (2011) Short Rotation Forestry: review of growth and environmental impacts. Forest Research Monograph, 2, Forest Research, Surrey; and Matthews et al. (2014) Carbon impacts of using biomass in bioenergy and other sectors: forests. DECC project TRN 242/08/2011.

[20] http://ukclimateprojections.metoffice.gov.uk/

2.1 Summary of key data generated from the ELUM project

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FIGURE 3

Mean soil GHG emissions over 40 years (relative to counterfactual land use), expressed as net GHG emissions per hectare across the UK

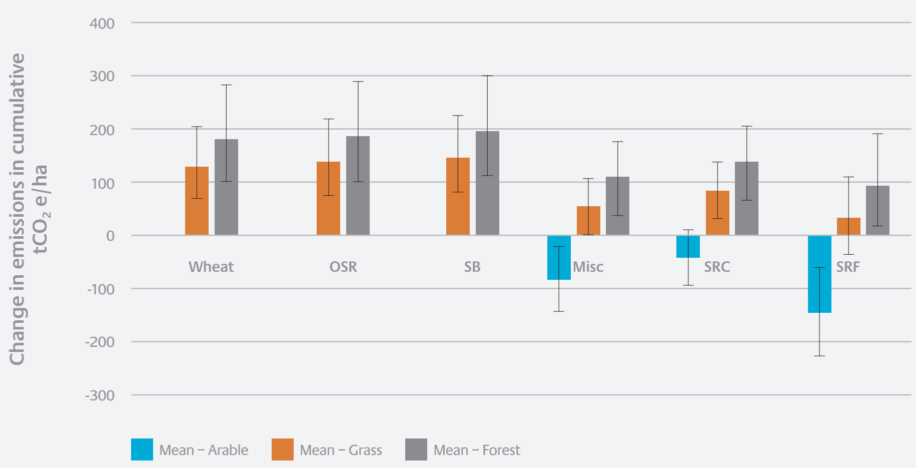
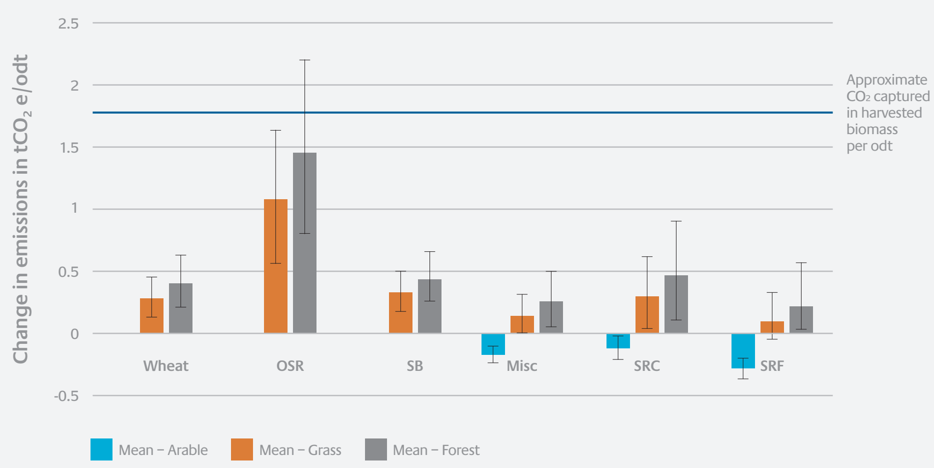


FIGURE 4

Mean soil GHG emissions over 40 years (relative to counterfactual land use), expressed as net GHG emissions per oven dried tonne (odt) of biomass produced across the UK



INTERPRETING THE GRAPHS

The columns denote the mean net changes in soil GHG emissions in tCO_2e modelled over 40 years, relative to continued arable, grassland or forest land use (the counterfactual). Emissions are expressed as either cumulative tCO_2e per hectare as in Figure 3, or per oven dried tonne equivalent (odt) in Figure 4. Blue bars denote a transition from arable land, orange bars denote transitions from grassland, and grey bars denote previously forested land. The error bars account for the difference between the mean soil GHG emissions and the mean soil GHG emission +/- 2SD. OSR = oilseed rape; SB = sugar beet; Misc = Miscanthus; SRC = short rotation coppice; and SRF = short rotation forestry.

For context, the approximate amount of atmospheric CO_2 captured per odt of harvested material is shown by the solid line[21] – this allows the effects of soil carbon changes to be compared against the amount of CO_2 captured in harvested biomass, in order to understand the relative importance of soil GHG emissions by feedstock type.

[21] Based on an average of approximately 47% carbon content in bioenergy crop material (generally between 45-50%, as seen in proximate analyses, and the Phyllis database https://www.ecn.nl/phyllis2/

2.1 Summary of key data generated from the ELUM project

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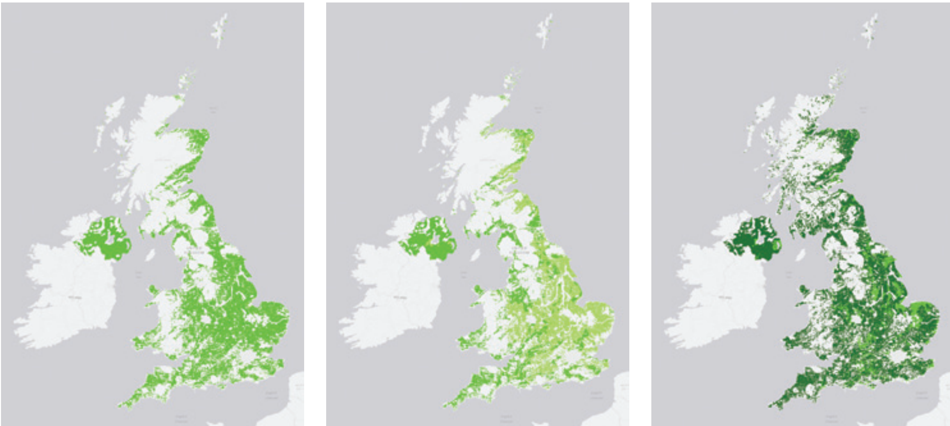
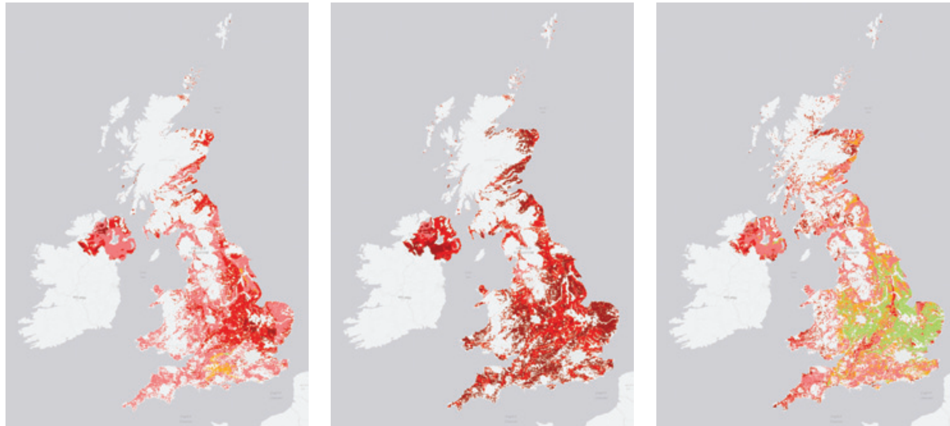
FIGURE 5

Spatial distribution of soil GHG emissions across the UK

A. Arable to Miscanthus | B. Arable to SRC-Willow | C. Arable to SRF (Poplar)



D. Grassland to Miscanthus | E. Grassland to SRC-Willow | F. Grassland to SRF (Poplar)



The maps above show the mean net soil GHG emissions for key transitions at the 1km²-level across the UK, i.e. approximately 250,000 cells. Across all maps; green denotes soil carbon gains (dark = more), amber denotes neutral transitions (minimal soil carbon losses), and light / dark red denote relatively larger soil carbon losses. White areas denote cells which were greater than two standard deviations (2SD) from the mean, or areas falling under land constraint masks, all of which were excluded from analysis. Generally more than 95% of data were within 2SD, with the exception of ‘arable to SRF’ transitions, which used 94% of the data, with 6% outliers excluded.

Cumulative net tCO_2e over 40 years, expressed as tCO_2e/odt

- > 0.25
- 0.125 to 0.25
- 0.025 to 0.125
- 0 to 0.025
- -0.125 to 0
- -0.25 to -0.125
- <-0.25

3. Combining insights and data from the ELUM and BVCM projects: assessing the scale of GHG emission savings arising from UK bioenergy value chains

The outputs from the ELUM project are estimates of cumulative soil GHG emissions arising from land-use change from Arable, Grass or Forest to bioenergy crops, expressed as tCO_2e/ha, or tCO_2e/odt. These measures will be useful and familiar to landowners, farmers and soil scientists, but are less tangible for policy makers and energy producers, who more frequently assess (bio)energy value chain emissions based on gCO_2e/MJ of final product. In addition, these soil GHG emissions need to be used to derive dLUC emissions associated with biomass feedstock production, in line with the EU Renewable Energy Directive (RED) methodology[22]. This seeks to capture changes to 'carbon stocks' caused by land use change from a reference (prior) vegetation type, to a new (actual) bioenergy vegetation. These carbon stocks are grouped into two main categories: i) the biomass material itself ("Cveg"), and ii) soil carbon stocks ("SOC"). Under the Cveg category, the RED methodology calculates net changes in carbon held within the vegetation over its' production lifecycle, taking account of total above- and below-ground plant material and litter fall. The inputs and outputs required to calculate a change in SOC have already been described in Figure 2 (page 14-15).

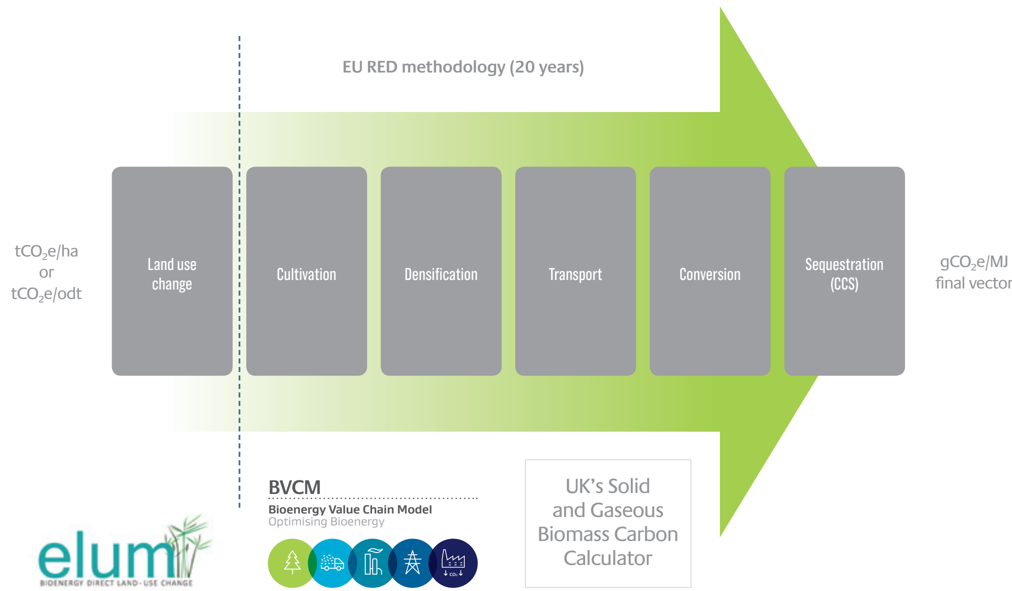
The RED states that land which prior to January 2008 was protected, wetland or a continuously forested area greater than one hectare, with trees higher than five metres and canopy cover greater than 30%, would not be considered suitable for conversion to bioenergy crops, unless that land after conversion had the same status as in January 2008. This means that transitions from forest to wheat, sugar beet, oilseed rape, Miscanthus and SRC-W would all be prohibited under the RED. Transitions from forest to SRF would be allowed, and would not be deemed a land use change.

ETI wanted to understand and interpret how significant soil GHG and wider dLUC emissions could be, relative to the GHG emissions of the whole value chain (system-level) – i.e. could it affect the level of carbon savings delivered relative to fossil fuel baselines?

The ETI commissioned E4tech to develop a tool to help provide this context and visualisation of the soil GHG and dLUC emissions derived from ELUM data, working with the University of Aberdeen, CEH, and Imperial College London to align key parameters and assumptions between ELUM and BVCM, such that the project outputs could be integrated. Modelled yields, measured litter fall, and above- and below-ground biomass data were taken from ELUM, and wider peer-reviewed literature where required. Average efficiency and GHG data for value chain components (cultivation, transport, densification, conversion, CCS) were extracted from BVCM (see Figure 6), with additional inputs from the UK's Solid and Gaseous Biomass Carbon Calculator[23] where appropriate. GHG emissions per mega-joule of final vector were calculated over 20 years using the EU RED methodology.

FIGURE 6

Diagrammatic representation of bioenergy value chain emissions considered



[22] EU RED methodology: https://ec.europa.eu/energy/sites/ener/files/2010_bsc_example_ghg_calculation.pdf

[23] https://www.ofgem.gov.uk/environmental- programmes/renewables-obligation-ro/information-generators/biomass-sustainability

3.1 Illustrating the impact of dLUC and CCS on UK bioenergy value chains

The ETI and E4tech have examined the impact of including dLUC emissions in over 75 UK bioenergy value chains to date, with examples for bio-heat, bio-electricity, bio-hydrogen, bio-methane and biofuels shown below.

INTERPRETING THE GRAPHS

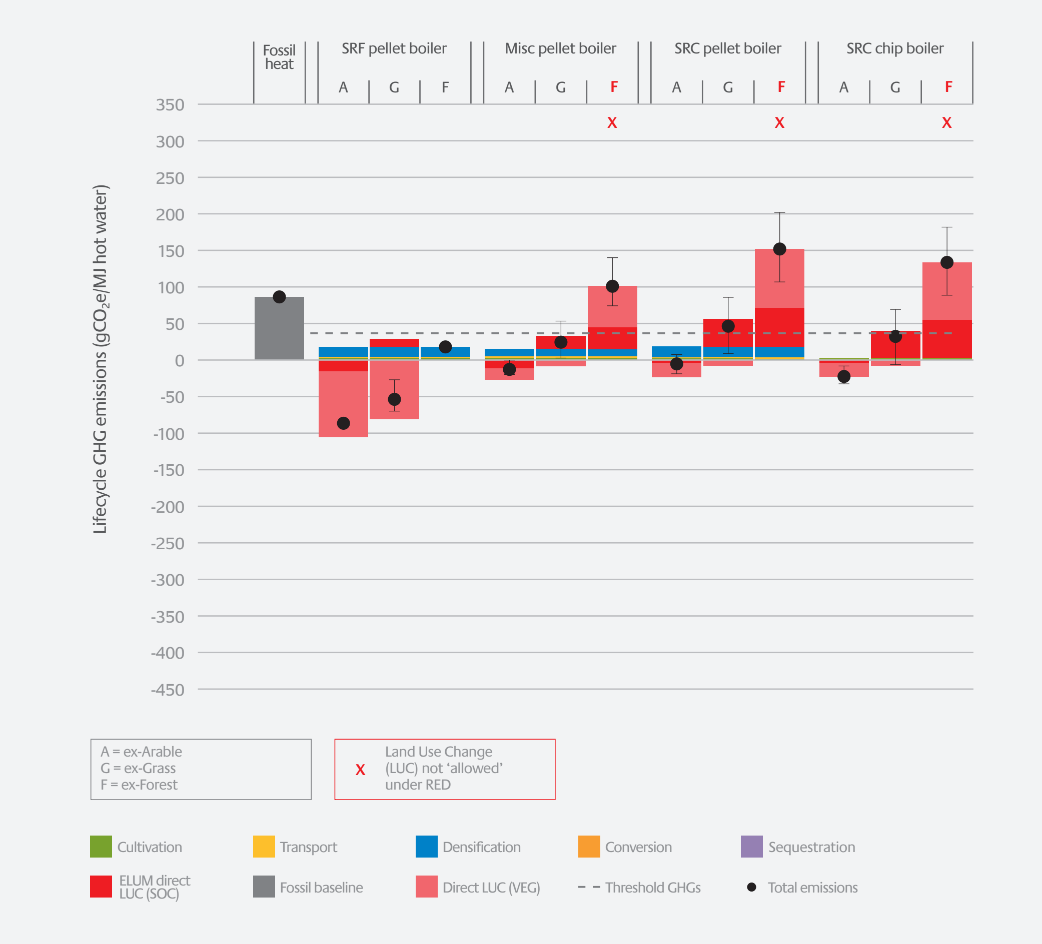
Total net GHG emissions over the 20 year accounting period used in the EU Renewable Energy Directive are shown by the black dots, and are based on the mean dLUC values ("Cveg" + "SOC") for that feedstock transition (e.g. Miscanthus from Arable). For all chains the error bars account for the difference between the mean SOC emissions (ELUM data) and the mean SOC emission +/- 2SD. N_2O emissions are accounted for in the cultivation emissions and CH_4 emissions are negligible. Fossil baselines (grey bar) are taken from current EU defaults. GHG thresholds (dotted grey line) indicate 60% saving vs. relevant fossil baseline. Along the x-axis, "A", "G" and "F" denote transitions from arable, grassland and forest respectively. Please note – under the RED, Forest to SRF transitions would not be deemed a land use change, and therefore no dLUC emissions are reported; whilst all other transitions from Forest would not be permitted (but the data is shown to illustrate why).

3.1.1 Bio-heat[24]

» dLUC emissions (Cveg + SOC) are material compared with other supply chain components in the absence of CCS.

» All heat chains are under the GHG threshold without including dLUC emissions, and including them highlights the significant savings possible from arable transitions. When using feedstocks from permissible LUC transitions under the RED, on average, bio-heat chains deliver approximately 105% GHG emission savings compared with the fossil baseline, although grassland to Miscanthus and SRC-W chains are much more marginal, since the mean values are close to or above the threshold. Understanding 'good' and 'bad' management practices would be important to ensure maximum GHG savings are delivered in those chains. SRF bio-heat chains offer the greatest potential to deliver GHG savings relative to the fossil baseline.

» The graph clearly illustrates that forest transitions to any bioenergy crops other than SRF would be detrimental in bioenergy value chains without CCS, validating the exclusion of these chains under the RED.



[24] For the SRF, Miscanthus and SRC pellet boilers we have assumed that the harvested crop was transported 20 km by truck to be pelleted and then a further 200 km in pelleted form to the boiler. For the SRC chip boiler we assumed the chips were transported 65km by truck. It was assumed that the truck used diesel fuel with a carbon intensity of 87.65 gCO_2e/MJ.

3.1 Illustrating the impact of dLUC and CCS on UK bioenergy value chains

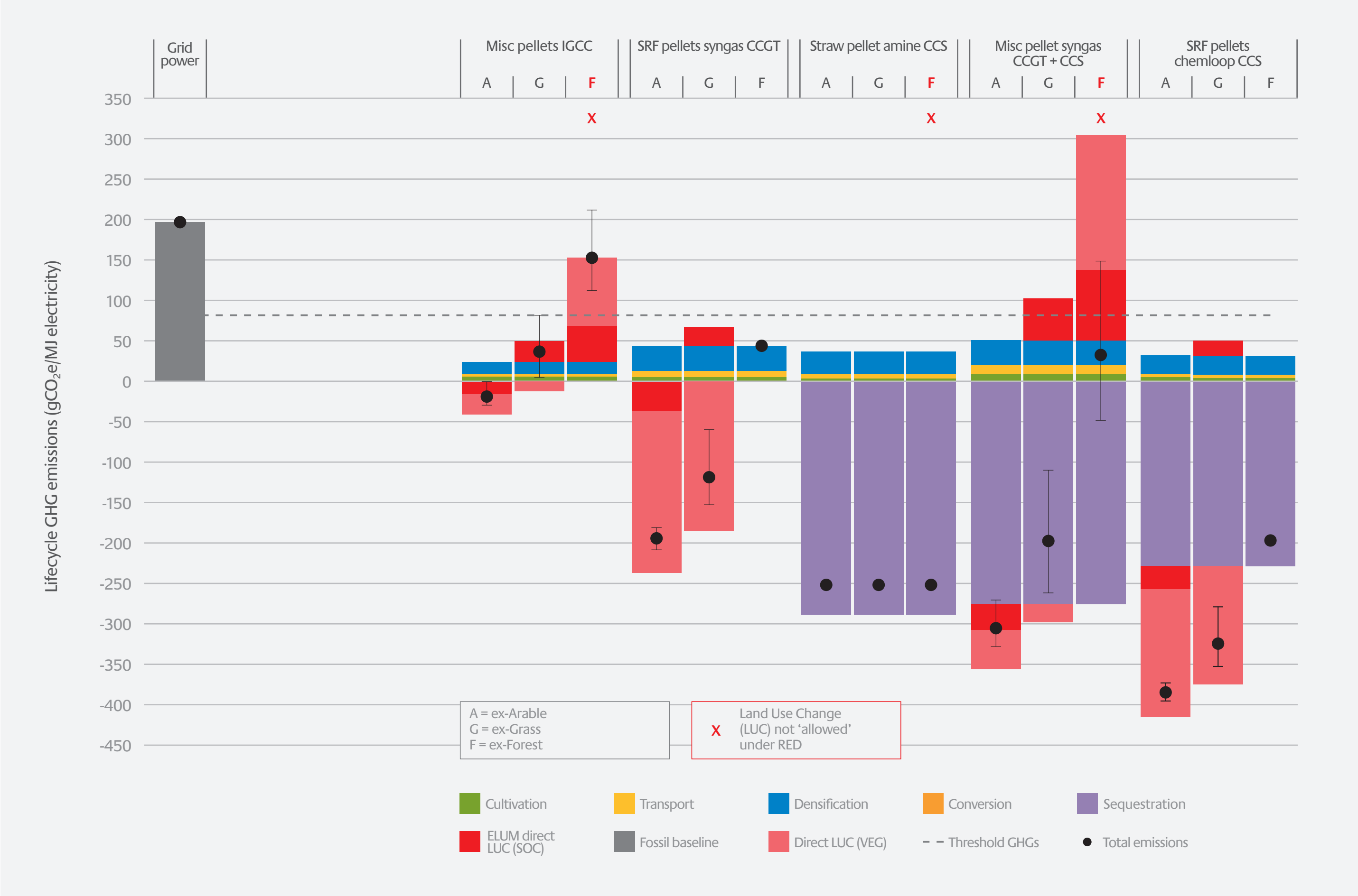
Continued »

3.1.2 Bio-electricity[25]

» **Most bio-electricity chains without CCS are well under the GHG threshold** without including dLUC emissions. Including them has a similar effect as seen in bio-heat chains. On average, permissible non-CCS chains deliver approximately 125% GHG emission savings compared with the fossil baseline.

» **Permissible chains with CCS retain their strong negative GHG emissions,** even including the error bars, due to the scale of carbon capture in CCS technologies. Therefore meeting the GHG threshold is not a challenge for permissible bio-electricity+CCS value chains, as on average they deliver approximately 235% GHG emission savings from the fossil baseline.

The GHG threshold shown here is 79.2g CO_2e/MJ electricity. All generators who use solid biomass and qualify for the Renewables Obligation (RO) must ensure that their GHG lifecycle emissions fall below this threshold[26]. In addition any dedicated biomass stations who joined the RO after March 2013 must meet a stricter average annual threshold of 66.7 gCO_2e/MJ electricity. The government has set out plans for this threshold to fall to 55.6 gCO_2e/MJ electricity in 2020 and to 50.0 gCO_2e/MJ electricity in 2025[27]. The chart to the right shows this is achievable in many UK bioenergy value chains.



[25] For all chains it is assumed that the raw crop is transported 20 km by truck to the pelleting mill. The pellets are then transported a further 200 km by truck to the conversion plant. It was assumed that the truck used diesel fuel with a carbon intensity of 87.65 gCO_2e/MJ.

[26] https://www.ofgem.gov.uk/publications-and-updates/renewables-obligation-sustainability-criteria-guidance-0

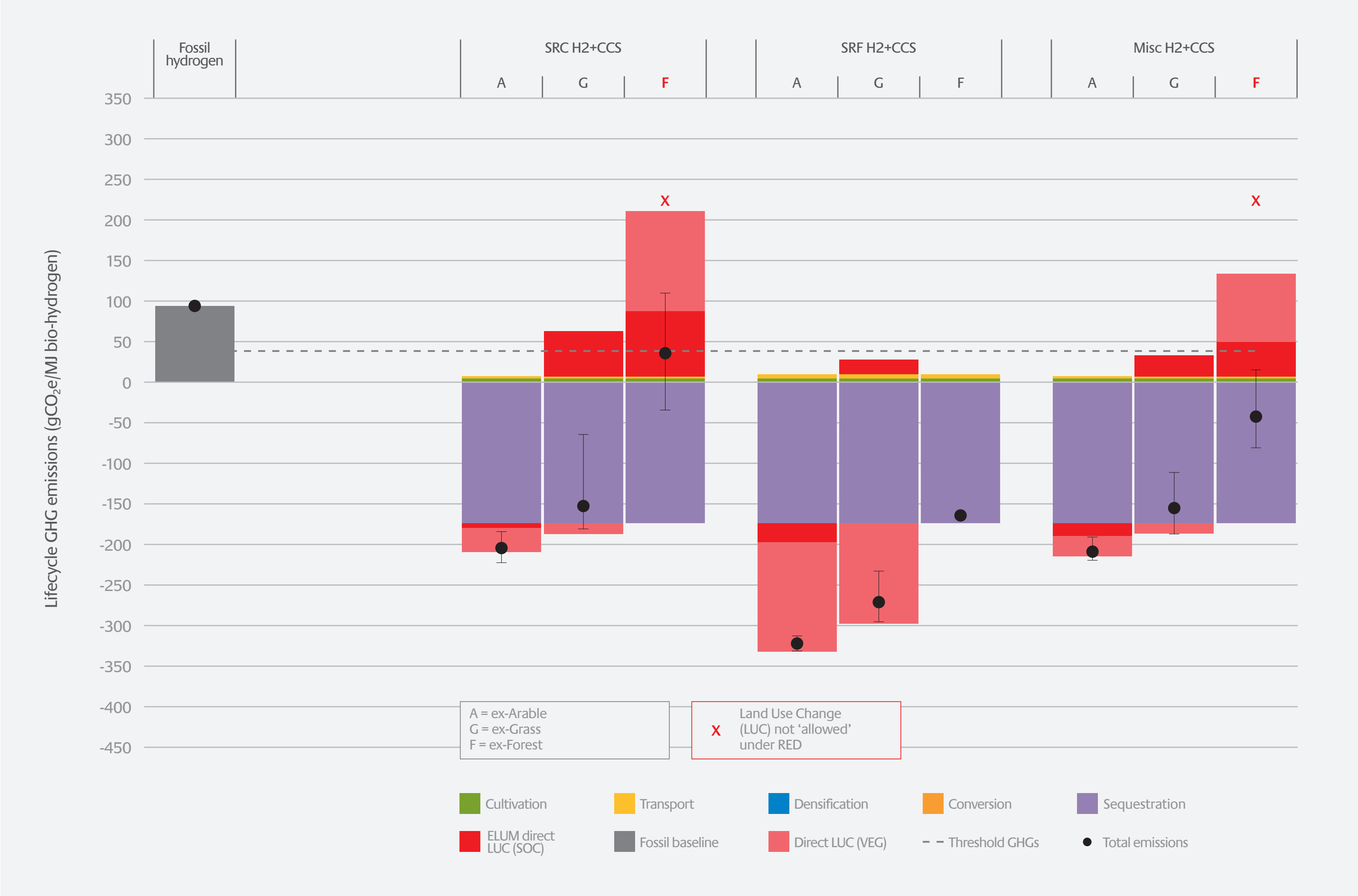
[27] https://www.ofgem.gov.uk/publications-and-updates/draft-guidance-renewables-obligation-greenhouse-gas-annual-averaging-mechanism

3.1 Illustrating the impact of dLUC and CCS on UK bioenergy value chains

Continued »

3.1.3 Bio-hydrogen[28]

- Bio-hydrogen is compared to a baseline of hydrogen made from fossil natural gas (via steam methane reforming). With no-CCS, permissible bio-hydrogen chains offer an average of 130% GHG emission savings compared with this baseline.
- **As with bio-electricity, the benefits of CCS outweigh all maximum dLUC emissions in permissible LUC transitions under RED, and on average H_2+CCS chains deliver 320% GHG emission savings from the fossil baseline.** This appears larger than bio-electricity+CCS chains, since the electricity sector baseline carbon intensity is currently much higher than hydrogen. Note that the actual negative emissions of the CCS component in bio-hydrogen chains are smaller than the CCS component of the bio-electricity chains, since the latter are generally less feedstock efficient, and hence they capture more CO_2 per MJ of final product.

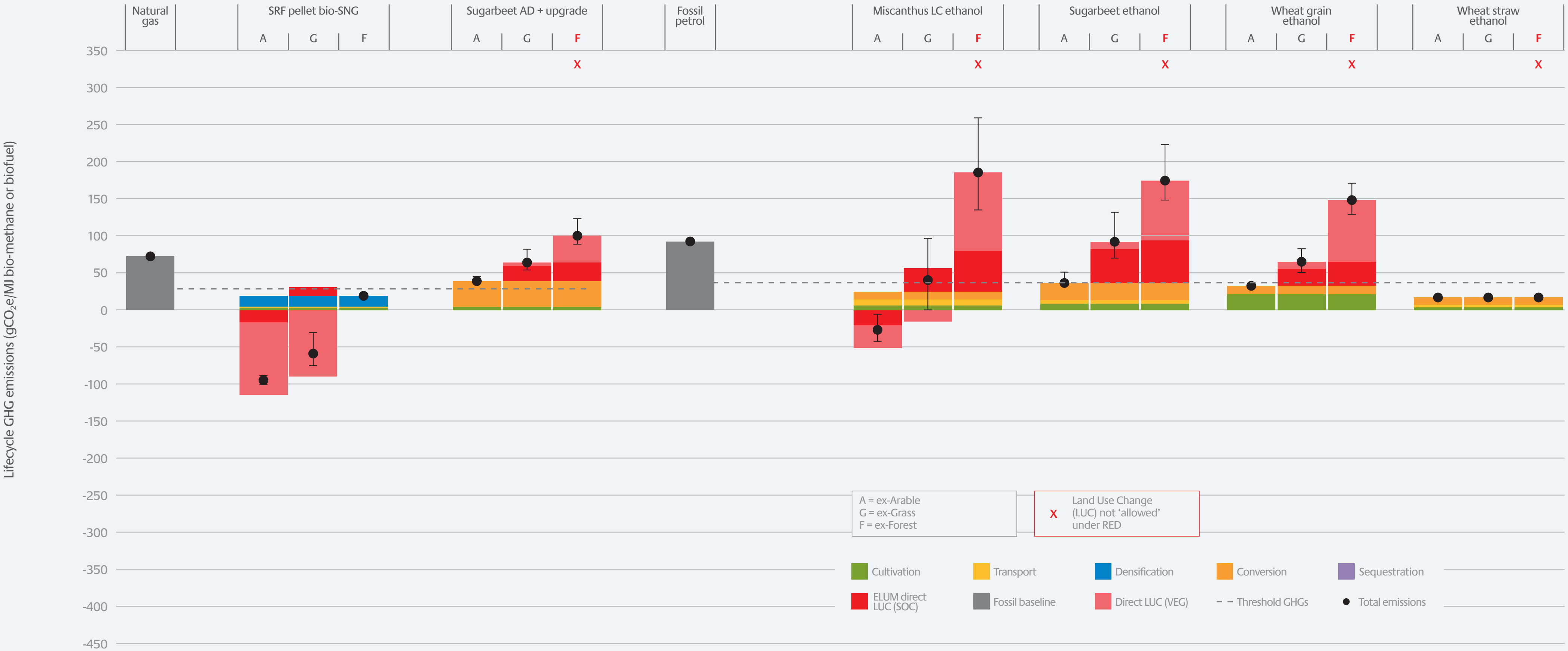


[28] For SRC and SRF H_2+CCS the raw feedstock is transported 200 km to the conversion plant by truck. The Miscanthus is transported 50 km by truck. It was assumed that the truck used diesel fuel with a carbon intensity of 87.65 gCO_2e/MJ.

3.1 Illustrating the impact of dLUC and CCS on UK bioenergy value chains

Continued »

3.1.4 Bio-methane and Biofuels[29]



[29] SRF pellet +Bio-SNG – The raw feedstock is transported 20 km to be pelleted and then a further 200 km to the bio-SNG plant. Sugar beet AD: The sugar beet is assumed to be transported 20 km to the AD plant. Miscanthus LC ethanol: The raw Miscanthus is transported 200 km to the ethanol plant. For sugarbeet, wheat grain and wheat straw to ethanol it is assumed that each crop is transported 80 km to the conversion plant. It was assumed that the truck used diesel fuel with a carbon intensity of 87.65 gCO_2e/MJ.

3.1 Illustrating the impact of dLUC and CCS on UK bioenergy value chains

Continued »

3.1.4 Bio-methane and Biofuels:

a) Bio-methane

Bio-methane is assumed to be used for grid injection, hence compared to a fossil natural gas baseline. Under the RED, 1G crops (wheat, oilseed rape, sugar beet) grown on arable land, and SRF grown on forest land, are assumed to have undergone no LUC, hence there are no dLUC emissions shown for these transitions.

- SRF pellet bio-synthetic natural gas (bio-SNG) chains offer an average of 160% GHG emission savings from the fossil baseline. As with all 2G bioenergy value chains, the savings delivered could be improved if poor management practices were avoided, or the pellet process was decarbonised
- Any bio-SNG value chains using purpose-grown 1G energy crops going to anaerobic digestion are likely to struggle to meet GHG thresholds even before adding dLUC emissions, due to large cultivation emissions and the assumed 3% methane slip in biogas production and upgrading ('conversion emissions')[30]. For this reason, we welcomed DECC's consultation on sustainability requirements around purpose-grown crops like maize being used in anaerobic digestion[31]

b) Biofuels

Transport is a hard sector to make GHG savings in, due to a low fossil baseline compared to electricity, and low efficiency chains which amplify upstream emissions.

- Once dLUC emissions are considered, biofuel value chains using purpose-grown 1G crops such as wheat and sugar beet are unlikely to meet the GHG threshold if grown on land converted from grassland or forest, and at best, GHG savings will be marginal where grown on arable land. Straw is an exception, as due to RED accounting rules it is counted as an agricultural residue and therefore dLUC emissions are not included, making the required GHG emission savings more achievable. This would not be the case where a dedicated crop such as maize or wheat has been planted specifically for energy
- The greatest savings in liquid transport fuels are delivered from 2G biofuel chains using arable land e.g. arable to Miscanthus transitions, here delivering approximately 125% GHG emission savings. It would be challenging to meet thresholds using biomass grown on land converted from grassland unless 'best practice / best available technologies' were followed (lower error bars), with significant improvements made in cultivation and conversion steps. Land use change from forest to any bioenergy crop other than SRF would not be permissible under the RED

[30] There are 5 main upgrading technologies: PSA, water scrubbing, chemical absorption, membranes and cryogenic separation, and their methane losses range from <0.1% up to about 4%; with 3.0% being typical for PSA and physical absorption technologies. The UK biomass and biogas carbon calculator uses default values from BioGrace II, being 1% losses in AD, plus 1.4% losses during upgrading, i.e. 2.41% total loss is the assumed default, or 2.0% if using actual data http://www.biograce.net/. Methane losses can always be reduced by paying for better kit - these are not immovable figures, but it would add to the overall cost of the value chain.

[31] https://www.gov.uk/government/consultations/consultation-on-a-review-of-the-feed-in-tariff-scheme

3.2 Most attractive UK bioenergy value chains in GHG terms

This work has quantified the impact of dLUC emissions and identified the following as 'attractive' UK bioenergy value chains which could be pursued with high confidence of them delivering significant GHG savings relative to fossil baselines at relatively low risk[32]

Bioenergy-CCS chains:

- Any bioenergy chain with CCS utilising 2G feedstock from LUC transitions permissible under the RED; with bio-hydrogen with CCS offering the greatest potential for GHG savings relative to current fossil baselines, but bio-electricity with CCS delivering greater amounts of captured CO_2/MJ overall[33]

Bioenergy (no CCS) chains:

- Many bioenergy value chains even without CCS technology, have the potential to deliver significant savings relative to the fossil baseline
- Bio-heat value chains utilising SRF feedstock, or Miscanthus and SRC-W grown on arable land, and those adopting 'best practice' for grassland transitions (i.e. most appropriate land and 2G crop selection, and minimal disturbance)
- Bio-electricity value chains using SRF, or Miscanthus grown on arable or grassland
- Bio-hydrogen value chains using SRF feedstock, or Miscanthus and SRC-W grown on arable land. Transitions to Miscanthus or SRC-W from grassland would need to pursue 'best practice' management practices to deliver GHG savings compared to the fossil baseline
- Bio-SNG value chains using SRF feedstocks
- 2G biofuel chains grown on arable land, using e.g. Miscanthus
- Many bioenergy value chains utilising waste or residues – where this is a genuine waste or residue, the RED accounting rules do not include any dLUC emissions associated with its production (as emissions only start from the point of collection). Therefore waste value chains typically offer substantial carbon savings. However, caution needs to be used when looking at value chains using similar feedstock, where they have been grown explicitly for the purposes of energy production. In these instances, a wider value chain assessment of the 'best yield and carbon savings for that land' would be advisable

[32] There is an assumption that iLUC emissions are either prevented or minimised by using marginal land for the bioenergy crops, or adopting 'sustainable intensification' practices such as improved yield varieties and good management practices during cultivation.

[33] This is in line with Matthews, R. et al. (2014) who found that the biggest negative emissions savings were delivered via biomass to power with CCS applications.

Overall, for many bioenergy value chains not paired with CCS, significant GHG savings can be made now by using 2G biomass feedstock grown on arable land, or some grassland sites, by matching feedstock type and management options carefully on a site-by-site basis, such that dLUC emission reductions, relative to the counterfactual land use, are delivered. Where bioenergy is deployed in combination with CCS, dLUC emissions become very small relative to the savings that can be delivered at the value chain level. Table 1 provides an illustration of types of UK bioenergy value chains and the carbon savings they could deliver relative to fossil fuels.

TABLE 1

Illustration of GHG savings (chain emissions plus dLUC emissions) delivered by example UK bioenergy value chains, using feedstock from land use changes deemed suitable/permissible under the RED.

End vector 20 YEAR	Chains where full range of emissions deliver more than 60% savings relative to fossil baseline, i.e. below the GHG threshold	Chains where mean emissions deliver 60% GHG savings, but higher error bar lies above threshold (i.e. would need to avoid poor practice to deliver > 60% savings)	Chains where mean emissions don't deliver 60% GHG savings, but lower error bar falls below threshold (i.e. need good or best practice to deliver > 60% savings)	Chains where full range of emissions above GHG threshold, and therefore value chain unlikely to deliver > 60% GHG savings relative to fossil baselines
Bio-Heat	» SRF pellet boiler (Arable, Grass, Forest) » Miscanthus pellet boiler (Arable) » SRC pellet boiler (Arable) » SRC chip boiler (Arable)	» Miscanthus pellet boiler (Grass) » SRC chip boiler (Grass)	» SRC pellet boiler (Grass)	
Bio-electricity	» Straw pellet amine CCS (Arable, Grass) » SRF pellets chemloopCCS (Arable, Grass, Forest) » Miscanthus pellet syngas CCGT + CCS (Arable, Grass) » SRF pellet syngas to CCGT (Arable, Grass, Forest) » Miscanthus pellet IGCC (Arable, Grass)			
Bio-hydrogen	» SRF H_2 + CCS (Arable, Grass, Forest) » Miscanthus H_2 + CCS (Arable, Grass) » SRC H_2 + CCS (Arable, Grass)			
Bio-methane	» SRF pellet bio-SNG (Arable, Grass, Forest)			» Sugar beet AD + upgrade (Arable, Grass)
Bio-fuel	» Wheat grain ethanol (Arable) » Wheat straw* ethanol (Arable, Grass) » Miscanthus LC ethanol (Arable)	» Sugar beet to ethanol (Arable)	» Miscanthus LC ethanol (Grass)	» Wheat grain ethanol (Grass) » Sugar beet to ethanol (Grass)

*Classed as a waste, so no emissions associated with biomass production are included in the calculation;

3.3 Developing a framework in the wider UK energy and agricultural context

Delivering the greatest value from bioenergy depends on the UK's ability to source sufficient biomass from sustainable sources, either domestic or imported. Domestic sources offer the greatest energy security and sustainability benefits in the longer-term, but the UK just doesn't have enough of its own biomass feedstock today to supply a commercially-viable large-scale bioenergy sector in the UK. As suggested previously[34], the most pragmatic approach would be to develop the sector now based on biomass imports derived from sustainable sources, so the key actors in the supply chain can 'learn by doing' in terms of logistics, handling, designing and operating bioenergy conversion technologies; whilst in parallel building up a strong and commercially-viable biomass feedstock supply chain in the UK.

The ETI commissioned YouGov to carry out a survey to understand public perceptions of bioenergy in Great Britain[35]. This demonstrated significant support for bioenergy, and highlighted that the public's opinion of bioenergy tended to improve, the more that biomass feedstock were sourced domestically, as opposed to imported[36].

Using the most appropriate yield maps and constraint masks, the ETI has estimated the amount of land potentially available in the UK where transitions to bioenergy crop production would be likely to deliver GHG-neutral or -beneficial soil GHG emissions. Combining this data with knowledge of the amount of domestic feedstock required over the next four decades, and knowledge of the value chains that deliver genuine carbon savings, enables us to develop a framework for expanding the UK bioenergy sector:

- In the absence of commercially-deployed CCS technology in the UK, 2G biomass feedstock should be grown on arable land, or grassland sites, where net GHG emissions would stay the same or decrease, and be used in the value chains identified as 'most-attractive' on Table 1, page 37. Approximately 4.9 million hectares of UK land could deliver these 'neutral' or 'beneficial' transitions to 2G bioenergy crops. By targeting 'marginal' land, selecting high-yielding mixtures of 2G bioenergy crops, and improving agricultural productivity as a whole (via sustainable intensification), iLUC emissions could also be avoided or at least minimised
- SRF feedstock is likely to offer the greatest GHG savings at the value chain level, and have the lowest overall dLUC emissions of all 2G bioenergy crops, particularly when grown on arable or grassland. SRF could be grown on forest land as it would not be counted as a land use change under the RED. However, in practice, felling existing forest and replacing with new forestry would result in some disturbance to the soil, but as long as the replacement crop is better yielding, net dLUC emissions are likely to remain negligible, since the increased vegetation cover would be expected to negate any soil carbon losses.
- The ETI's analysis suggests that a planting rate of 30,000 hectares per annum would be sufficient to put us on the trajectory for 2050 bioenergy and negative emission targets over the next two decades[37]. This amounts to 300,000 hectares over the next ten years, i.e. 6% of the land identified here as suitable from an emissions point of view, 4.8% of the total croppable area of the UK, and only 1.6% of total agricultural land[38]. The scale of this land use conversion over time is illustrated in Figure 7 (page 42-43), relative to different types of UK land today
- In parallel, the targeted conversion of a small amount of grassland, e.g. up to 1,000 hectares of 2G bioenergy crops per annum, would enable practitioners and scientists to improve the understanding around grassland management practices including timing of harvests; above- and below-ground biomass allocations (in order to understand how much carbon is removed at harvest, and how much stays in the living biomass structural pool in the soil); and fuller life-cycle assessments of different grassland types and uses. The evidence generated from 'learning by doing' would enable us to better identify grassland sites where it is highly beneficial to convert to 2G bioenergy crops, taking into account emission savings and wider ecosystem services benefits. The work presented here suggested grassland to SRF transitions should be the initial focus.
- By 2035, CCS technology should have been commercially deployed and tested in the UK. This technology, combined with the evidence generated from the targeted planting described above, facilitates a wider and more confident utilisation of grassland for 2G biomass production, knowing that it delivers significant GHG savings at the value chain level when combined with CCS. This would release a further ~3.8 million hectares of UK land that could be used to deliver net GHG emission savings at the system level.

[34] ETI (2015): Enabling UK biomass. http://www.eti.co.uk/wp-content/uploads/2015/09/3504-Biomass-Insights-Lores-AW.pdf

[35] Source: YouGov plc (2015) © All rights reserved. All figures, unless otherwise stated, are from YouGov Plc. Total sample size was 3,105 adults. Fieldwork was undertaken between 21st-24th August 2015. The survey was carried out online. The figures have been weighted and are representative of all GB adults (aged 18+).

[36] Support for bioenergy amongst respondents was high, with 72% supporting 'biomass to energy' and 81% supporting 'waste to energy' applications. Respondents were asked to reflect whether their opinion on bioenergy would improve, worsen or stay the same if they were told that a) 'the UK is able to source about half of its own supply of biomass domestically' and b) that 'the UK is able to source all of its biomass domestically'. For (a), 38% of respondents said their opinion would slightly or significantly improve; and for (b) 67% of respondents said their opinion would slightly or significantly improve. For context, under (a) 12% said their opinion would worsen, 37% stay the same and 13% 'don't know'; and under (b) 2% said it would worsen, 18% stay the same and 13% 'don't know'. Additionally they were asked how their opinion would change if 'the UK has to import all of its biomass from overseas' – 7% said it would improve, 16% stay the same, 63% worsen and 15% 'don't know'.

[37] Based on average BVCM scenarios that deliver approximately 6% of UK 2050 energy, and a substantial amount of negative emissions in 2050 from domestic biomass supplies produced on minimum land areas.

[38] Defra (2015): Agriculture in the United Kingdom 2014. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/430411/auk-2014-28may15a.pdf

3.3 Developing a framework in the wider UK energy and agricultural context

Continued »

This framework could deliver significant volumes of biomass feedstock, enabling the production of substantial negative emissions and energy production by 2050. It is presented pictorially in Figure 7 (page 42-43). If pursued, it could limit the amount of marginal arable land being used to 600,000 hectares, and target optimal grassland areas, that collectively deliver the greatest ecological, environmental and economic benefits to the UK. For context, the average annual absolute change in harvested wheat area is 141,000 hectares, with the largest annual change of 451,000 hectares seen in 2000/0139. This highlights that the current agricultural landscape is perhaps more dynamic than is commonly perceived.

There is an increasing body of case studies[40] where farms have converted a percentage of their land (mainly 'marginal' arable, and some grassland) to 2G bioenergy crops such as Miscanthus and SRC-W, to deliver greater farm productivity, profitability and diversity of income, and wider environmental benefits. This highlights the need to improve our knowledge of the much-quoted, but often mis-understood concept of 'marginal' land. Land may be 'marginal' to a farmer or land-owner for a number of reasons: under-utilised, poorer-quality soil or 'agricultural grade', problems with access or ability to use conventional machinery, problems with water-logging or weeds, pests and diseases, such as black grass – all reasons which may require significant chemical or management interventions. Bioenergy crops offer the potential to provide a more diverse, less intensive, environmentally-beneficial land use whilst delivering economic yields[41] and substantial GHG savings to the UK. ETI is collecting further evidence of such case studies through our "Refining Estimates of Land for Biomass" (RELB) project.[42] More work also needs to be undertaken to understand how best to integrate SRF into the agricultural landscape, in order to maximise the wider environmental, economic and social benefits delivered, in addition to the substantial GHG emission savings identified earlier.

There are currently 160,000 hectares of uncropped arable land, which includes all arable land not in production, including GAEC12 land, game strips, wild bird cover and game cove[43]. Several pieces of work by ELUM project participants and others have identified the potential benefits of second generation bioenergy crops in delivering biodiversity and wider ecosystem service benefits, including hazard regulation, disease and pest control, improving water and soil quality, and acting as wildlife/game cover[44]. This raises the potential opportunity of utilising some of this 'uncropped arable land' for bioenergy, which can continue to deliver the current ecosystem services, such as game cover, or be a substitute crop in nitrate-vulnerable-zones (areas where nitrogen inputs should be minimised).

In 2013, over 50,000 hectares of UK agricultural land were used for bioenergy, of which 42,000 hectares were 1G crops used for transport fuels[45]. In addition, Defra estimates that 29,400 hectares of maize was grown in the same year for exclusive use in anaerobic digesters. The analysis undertaken by the ETI clearly raises questions as to whether the bioenergy value chains currently 'using' that land for feedstock production really offer the 'best use' of that land, given the system-driver of GHG savings.

Spatially, it is possible to identify the optimal locations for new plantings, taking in to account a) where in the UK bioenergy crops could be produced with minimal dLUC emissions; and b) where in the UK the feedstock would be best utilised from a wider energy system perspective. The key results are shown in Figure 8 (page 44-45), based on land use transitions to 2G bioenergy crops which would deliver either no change in soil carbon, or soil GHG emission savings (i.e. neutral to beneficial LUC transitions).

From an economic and emission optimisation point of view, the areas most suited to bioenergy deployments, and the most cost effective locations for bioenergy-with-CCS deployments, are the south and east of England for Miscanthus; the west and north-west of England for SRC-W; and central England for SRF. As can be seen from Figure 8, there are significant areas of overlap between the most favourable locations for minimising soil GHG emissions, and the preferred economically optimal locations identified in BVCM.

[39] Defra 2014: data based on year-on-year average changes between 1984 and 2013. https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom Table 7.2.

[40] For example, Terrevesta grower case studies – available at: http://www.terravesta.com/Ed-Green

[41] Jones, M.B. et al. (2015) Morphological and physiological traits for higher biomass production in perennial rhizomatous grasses grown on marginal land. GCB Bioenergy, 7, 375-385. http://dx.doi.org/10.1111/gcbb.12203

[42] Refining estimates of land for biomass production in the UK. RELB Project led by ADAS. http://www.eti.co.uk/project/refining-estimates-of-land-biomass-relb/

[43] The aim of GAEC12 land under Cross Compliance, is to maintain land not in production in 'Good Agricultural and Environmental Condition' http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=1QQUSGMWSS.0IRLJGRQ9MUANX

[44] McCalmont, J.P. et al (2015) Environmental Costs and Benefits of Growing Miscanthus for Bioenergy in the UK. GCB Bioenergy http://dx.doi.org/10.1111/gcbb.12294; and Holland, R.A. et al. (2015) A synthesis of the ecosystem services impact of second generation bioenergy crop production, Renewable and Sustainable Energy Reviews, 46, 30-40. http://dx.doi.org/10.1016/j.rser.2015.02.003

[45] The land area used for bioenergy comprised 8,000 hectares of oilseed rape; 8,000 hectares of sugar beet; 26,000 hectares of wheat; 7,000 hectares of Miscanthus and 3,000 hectares of short rotation coppice (Defra UK agricultural statistics: http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/434098/nonfood-statsnotice2012-10jun15.pdf)

3.3 Developing a framework in the wider UK energy and agricultural context

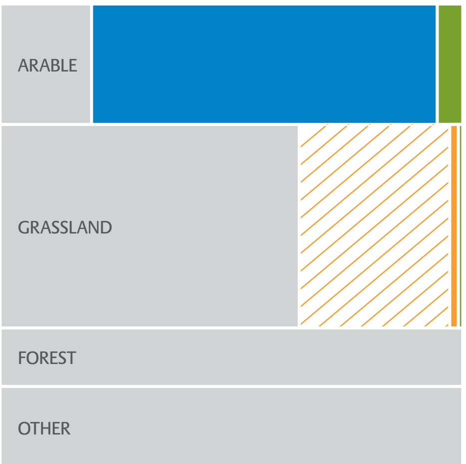
Continued »

FIGURE 7

Diagrammatic representation of the amount of land suggested for biomass production in the UK, ramping-up production over the next 40 years.

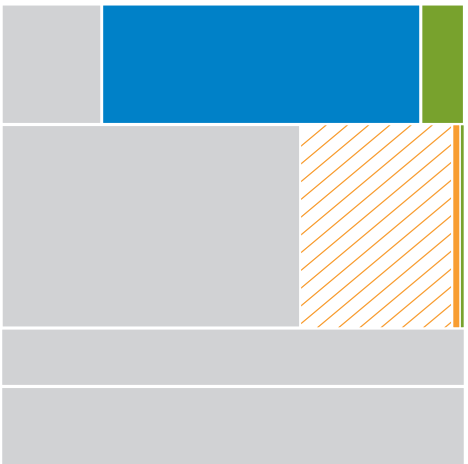
Total 'box' area denotes all of UK land area; grey denotes land excluded under constraint masks; blue denotes 'suitable' arable land (from dLUC perspective); orange denotes 'suitable' grassland – with hatched orange denoting available grassland which currently has higher uncertainty over dLUC emissions; green denotes area converted to 2G bioenergy crops as per framework outlined.

2015 - 2025



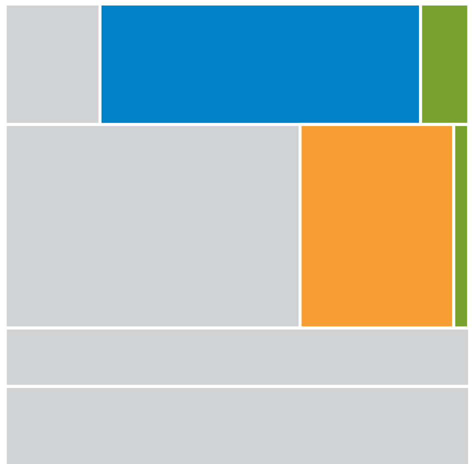
- » CCS not yet operational
- » Plant 30,000 ha per annum
- » Target 'marginal' arable land
- » Small amount of grassland used to progress understanding of management practices, carbon stock in biomass; counterfactual LCAs
- » In total, ~310,000 ha planted (green boxes)

2025 - 2035



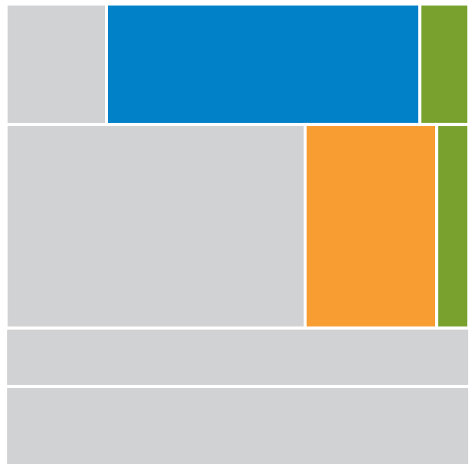
- » CCS not yet operational
- » Plant 30,000 ha per annum
- » Target 'marginal' arable land
- » Small amount of grassland used to progress understanding of management practices, carbon stock in biomass; counterfactual LCAs
- » In total, ~620,000 ha planted (green boxes)

2035 - 2045

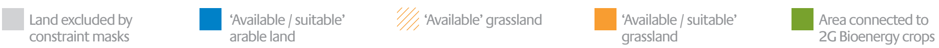


- » CCS becomes operational
- » Plant 30,000 ha per annum
- » Switch new plantings to grassland, since dLUC emissions are 2nd order relative to negative emissions delivered through bio CCS.
- » In total, ~920,000 ha now planted (green boxes)

2045 - 2055



- » CCS operational
- » Plant 30,000 ha per annum
- » Further plantings on grassland, since dLUC emissions are 2nd order relative to negative emissions delivered through bio-CCS.
- » Biomass production integral part of optimised UK agricultural sector
- » In total, ~1,220,000 ha now planted (green boxes)



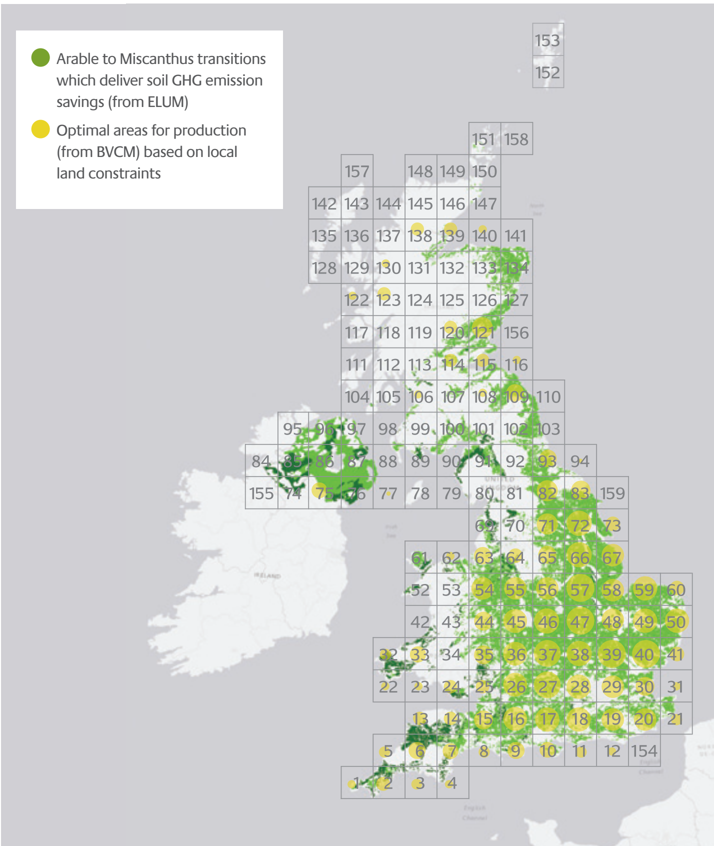
3.3 Developing a framework in the wider UK energy and agricultural context

Continued »

FIGURE 8 (I)

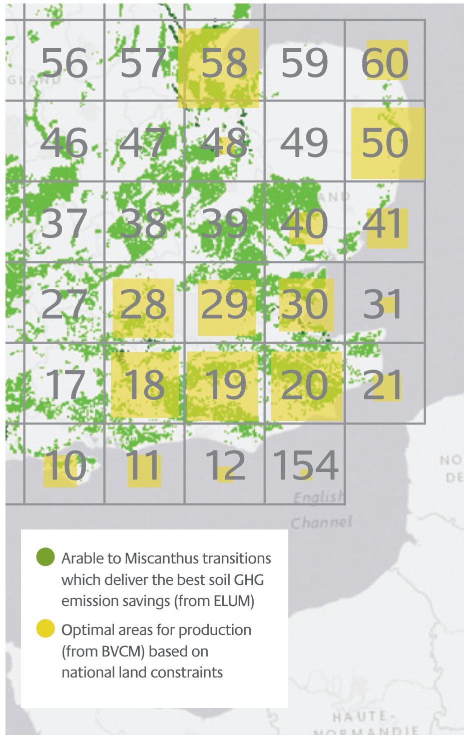
Spatial deployment of Miscanthus production from arable land in the UK based on maximising soil GHG emission savings, and taking account of optimal production areas from BVCM.

On the left: all areas where arable to Miscanthus transitions are likely to deliver net soil GHG savings (darker green being better than lighter green, but all are below 0tCO_2/odt), overlain with optimal production areas as identified in BVCM, based on local land constraints. On the right: the areas likely to provide the best soil GHG savings (of at least -0.21 tCO_2e/odt), with preferential Miscanthus production areas as identified in BVCM based on national land constraints, overlain.



Each map shows preferred planting areas shown as cumulative net tCO_2e/odt over 20 years, expressed as tCO_2e/odt

- 0 to 0.025
- -0.125 to 0
- -0.25 to -0.125
- <-0.25

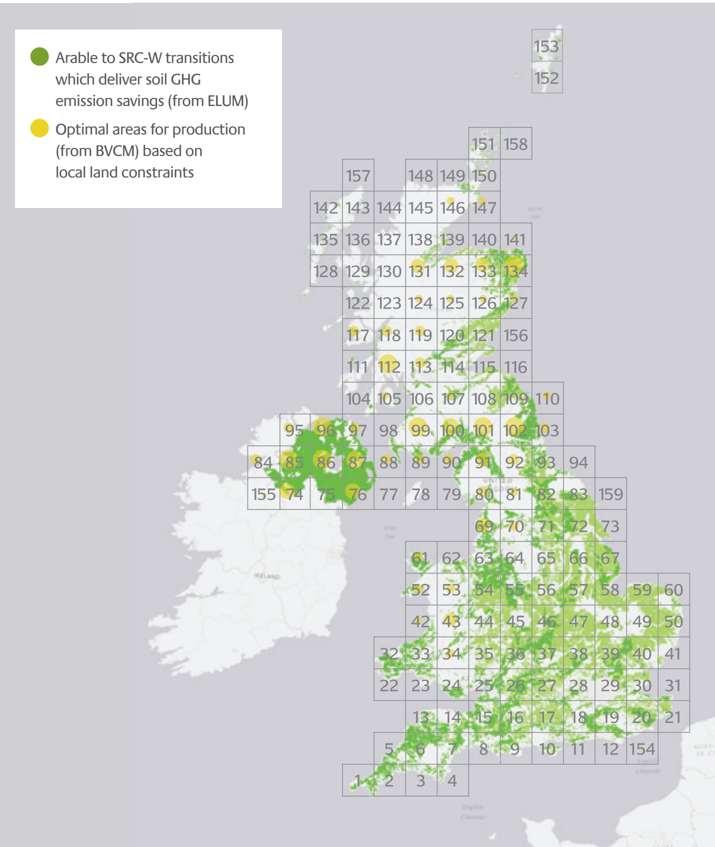


3.3 Developing a framework in the wider UK energy and agricultural context

Continued »

FIGURE 8 (II)

Spatial deployment of SRC-W production from arable land in the UK based on maximising soil GHG emission savings, and taking account of optimal production areas from BVCM.



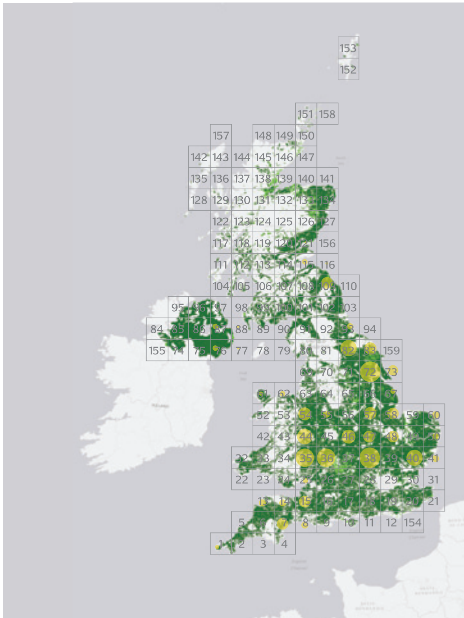
Each map shows preferred planting areas shown as cumulative net tCO_2e/odt over 20 years, expressed as tCO_2e/odt

- 0 to 0.025
- -0.125 to 0
- -0.25 to -0.125
- <-0.25

FIGURE 8 (III)

Spatial deployment of SRF production from arable and grassland in the UK based on maximising soil GHG emission savings, and taking account of optimal production areas from BVCM.

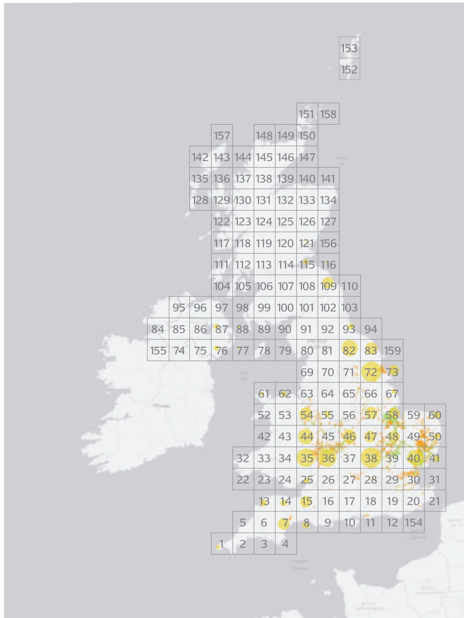
A. Arable to SRF



Arable to SRF transitions which deliver soil GHG emission savings (from ELUM)

Optimal areas for production (from BVCM) based on local land constraints

B. Grassland to SRF



Grassland to SRF transitions which deliver soil GHG emission savings (from ELUM)

Optimal areas for production (from BVCM) based on local land constraints

3.4 Next steps

Making a decision in the next few years to support a controlled roll-out of UK biomass production is crucial: an early decision would provide the time required to identify the very best ways of producing biomass to maximise the GHG savings delivered, enhance ecosystem services, and maximise the overall productivity of the land including food production. The longer a decision is delayed, the more rapid the roll-out would need to become, limiting the UK's ability to identify optimal approaches and share best practice.

Taking these decisions and actions over the next 5-10 years protects the UK's option to pursue the lowest cost route to delivering the UK's climate change commitments by 2050. It also provides time to develop a framework to optimise the efficiency, economic and environmental performance of the UK agricultural sector as a whole.

This was an explicit recommendation arising from the Gallagher Review (2008), and remains pertinent today. The agriculture sector was responsible for 10% of UK greenhouse gas end-user emissions in 2013; and in particular, 48% of all methane emissions and 79% of all nitrous oxide emissions[46]. Given these high GHG emissions, it would be prudent to ensure all agricultural land use activities are treated in the same way, as there is no point pursuing one activity for its ability to deliver GHG savings, if the GHG impact of other activities are ignored. Optimising the efficiency, economic and environmental performance of the UK agricultural sector as a whole, not just food production, should be a primary focus for research and innovation programmes such as the AgriTech Strategy[47].

Coordinating the UK agricultural sector to realise the significant benefits of greater biomass production will require policy changes to make it practical and effective. In the first instance, these policy changes could actually be quite modest to deliver the 30,000 hectares per annum suggested. Support from the UK Government would accelerate the value and learning achieved; enabling the evidence and confidence to be developed to move forward with the implementation of a national framework. This support is required to give a clear message to agricultural practitioners and industry, that the production and use of sustainable biomass is valued as an integral part of meeting our carbon budgets and 2050 GHG reduction targets.

Further research, and the targeted learning from commercial plantings discussed earlier, will feed in to the development of a framework to enhance national agricultural productivity. ETI's BVCM toolkit is now being used in two EPSRC Supergen Bioenergy projects[48], which seek to a) examine the optimal production of food and bioenergy crops in the UK, incorporating data on wider ecosystem service benefits and impacts, in order to identify optimal solutions to agricultural land use more broadly; and b) continue to collect GHG and soil carbon data from commercial sites.

ETI will also continue to improve our understanding of the suitability of land for biomass production through the RELB project, which will feed in to ongoing analysis of optimal bioenergy value chains. The ELUM data is being directly incorporated within the BVCM toolkit, which will enable us to continue to refine our estimates of the GHG emission savings that can be delivered from different value chains, and ultimately the amount of land available for conversion. Part of this future work will examine the impact of different sustainable intensification scenarios, and to identify ways of minimising any iLUC emissions which may arise from utilising 600,000 hectares of marginal arable land.

This further research would be significantly enhanced by more granular data on the current yields of different agricultural crops around the UK, and livestock productivity, all of which are currently difficult to obtain in a consistent manner across the sector. This could potentially be done via an update of the UK's Food Security Assessment[49], which was last completed in 2007[50]. The benefit of current Common Agricultural Policy restrictions on land use change may be debatable (e.g. the limit of 5% change in total grassland area), if alternative land uses were shown to deliver GHG savings and be beneficial to wider ecosystem services, without diminishing wider food production potential. Equipped with these data and evidence of wider agricultural GHG emissions[51], a more strategic framework for optimal agricultural land use in the UK could be developed.

[46] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416810/2014_stats_release.pdf

[47] https://www.gov.uk/government/publications/uk-agricultural-technologies-strategy/uk-agricultural-technologies-strategy-executive-summary

[48] EPSRC SUPERGEN Bioenergy Challenge Project EP/K036734/1: http://www.supergen-bioenergy.net/research-projects/bioenergy-value-chains--whole-systems-analysis-and-optimisation/; and the MAGLUE project (EP/M013200/1): http://www.maglue.ac.uk/

[49] UK Food Security Assessment: Detailed Analysis http://www.ifr.ac.uk/waste/Reports/food-assess-analysis-0908.pdf

[50] with minor updates in 2010.

[51] For example, from Defra's GHG Platform programme for example http://www.ghgplatform.org.uk

4. Conclusions

- CCS is a game-changer. Bioenergy value chains with CCS render dLUC emissions of second-order importance, since virtually all CCS value chains using 2G bioenergy crops grown in the UK would deliver substantial negative emissions to the UK. This work strengthens the link between biomass and CCS, which remains the only credible route to deliver genuine negative carbon emissions at the scale necessary to meet the UK's 2050 GHG emission reduction targets
- Bioenergy can offer flexibility for low carbon energy supply in a future UK energy system, since numerous bioenergy value chains can deliver genuine system-level carbon savings, across all key vectors of power, heat, liquid and gaseous fuels
- If bioenergy is deployed without CCS, dLUC emissions can be material, either contributing GHG emission savings or producing additional emissions at the value chain level, depending on choice of crop type, location, and ultimate use in the energy system. This work has reiterated the need to assess emissions across the whole value chain, and not just view feedstock or land use change emissions in isolation, in order to judge the scale of carbon savings achieved
- Bioenergy value chain emissions can be further reduced by decarbonising parts of the chain – such as using fewer inputs to the supply chain, or using low-carbon energy to produce the processed biomass forms such as pellets
- Sustainability, security of supply and public acceptability can be increased if the UK doesn't rely entirely on biomass imports, and instead uses a mixture of 'home-grown' and imported feedstock. This requires action and support to expand the UK's nascent biomass production sector, incentivising the production of sustainable feedstock in ways that fit with current farming and land management systems, ultimately maximising land use and value chain productivity
- The evidence for system-level carbon savings are sufficiently strong and widespread across the UK, to support the implementation of a national policy framework for large-scale biomass production, targeting second generation bioenergy crops (Miscanthus, Short Rotation Forestry and Short Rotation Coppice) production on suitable 'marginal' arable land today
- In parallel, a small amount of targeted grassland transitions to 2G bioenergy crops, especially to SRF, should be pursued in order to improve our understanding of how to maximise the GHG savings delivered, alongside wider ecosystem services and increases in overall productivity. Supporting these transitions today would ensure that by 2035 when CCS becomes operational, grassland can be converted to 2G bioenergy crops with confidence
- Planting 30,000 hectares a year of 2G bioenergy crops over the next decade would keep us on the trajectory for scaling up domestic biomass production out to the 2050s. These 300,000 hectares represent only 6% of the low-risk 'suitable' land identified from a GHG emissions viewpoint; only 4.8% of the total croppable area of the UK; and only 1.6% of total UK agricultural land[52]. This planting would ideally be on marginal arable land, or grassland in appropriate locations. A ramp-up of this scale is comparable to existing arable cropping land use changes, and would enable the benefits of integrating biomass production alongside food production to be demonstrated. It is also not without precedent, since oilseed rape had reached a peak of 750,000 hectares by 2012, with a peak annual increase in planted area of 110,000 hectares (in 2002/3)[53]
- The GHG benefits of increased planting of 2G bioenergy crops is relatively immediate, since crops that are well-matched to sites can start acting as net carbon sinks relatively quickly. Given the long lead times for market development and technology deployment, and the time from establishment to commercial harvest being 3-4 years for Miscanthus and SRC, and at least 7 years for SRF, we need to invest now to realise the potential benefits of bioenergy, and domestic biomass in particular. It is not necessary to have the CCS capacity in place beforehand
- Taking these decisions and actions over the next 5-10 years protects the UK's option to pursue the lowest cost route to delivering it's climate change commitments by 2050. It also provides time to develop a framework to optimise the efficiency, economic and environmental performance of the UK agricultural sector as a whole

[52] In 2014 the croppable areas of the UK was 6,278,000 hectares; the Utilised Agricultural Area was 17,240,000 hectares and the Total Agricultural Area was 18,456,000 hectares (Defra, 2014): https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/388470/structure-jun2014final-UK-18dec14.pdf

[53] Defra (2015) Chapter 7, Agriculture in the UK. https://www.gov.uk/government/statistical-data-sets/agriculture-in-the-united-kingdom

Glossary

Term	Definition
1G (first generation) bioenergy crops	First generation bioenergy crops. Generally refers to arable crops such as wheat, maize and oilseed rape which were first used to make biofuels
2G (second generation) bioenergy crops	Second generation bioenergy crops. Generally refers to 2G biomass sources such as Miscanthus, SRC and SRF
Carbon partitioning	A technique used to determine the relative quantities of carbon in different parts of a given system
Carbon savings (system level)	A measure of the reduction in greenhouse gases released as a result of generating energy from biomass as opposed to its fossil fuel equivalent
Control sites	Sites used in the ELUM project which did not undergo land use change. They were each paired with a site which had converted to bioenergy for comparison
Conversion emissions	Emissions associated with Conversion Technologies such as the methane emissions ('slippage') from anaerobic digesters
Counterfactual	The alternative scenario to which something is compared. For example, in ELUM, transitions from arable to bioenergy crops were compared to a counterfactual of continued arable land use
Cultivation emissions	Emissions associated with 'cultivating' the land i.e. growing an energy crop (e.g. fertiliser application & emissions from tractors used during ploughing and harvesting)
Densification emissions	Emissions associated with the pre-treatment of biomass feedstock to make it more energy dense, for example through pelleting
Direct Land Use Change (dLUC)	The conversion of land from one agricultural use (prior or reference land use) to another (new or actual land use), e.g. from grassland to short rotation forestry
dLUC emissions	The change in greenhouse gas emissions as a result of direct land use change. This comprises changes in the carbon stock stored in the soil and vegetation (above- and below-ground biomass material and litter), as well as changes in other GHG emissions, such as methane and nitrous oxide, as a result of the land use change
Ecosystem services	Benefits obtained from ecosystems. The UN's Millennium Ecosystem Assessment groups these benefits into four categories: provisioning (e.g. food production), regulating (e.g. climate regulation), supporting (e.g. crop pollination) and cultural (e.g. recreational benefits)
GHG emissions	Greenhouse gases emitted during a stage in the value chain, such as biomass production (from the soil or biomass material) or transportation activities
GHG (emission) savings	Net GHG emission savings denotes an overall reduction in greenhouse gas emissions achieved across a value chain in any given scenario compared with its counterfactual, either through an increase in carbon stocks via increased soil carbon (SOC) or decreased soil GHG fluxes; an increase in biomass material (Cveg); or a reduction in value chain GHG emissions
GHG flux(es)	The exchange of greenhouse gases (CO_2, N_2O and CH_4 here) between different parts of the ecosystem being emitted to atmosphere

Term	Definition
GHG thresholds	The limit on the emissions that can be released when producing bioenergy and still be eligible for government subsidies. The threshold is different for different energy vectors but is typically set at 60% below the fossil fuel baseline
Global Warming Potential (GWP)	A relative measure of how much heat a greenhouse gas traps in the atmosphere over a given length of time. The GWP of Carbon Dioxide is 1. In this paper we used GWP figures over 100 years for CO_2 (1), N_2O (296) and CH_4 (23). The GWP figure for a given greenhouse gas can be multiplied by the mass of that gas to show how much CO_2 would have the same warming effect over the same time scale (units: tCO_2e)
Indirect Land Use Change (iLUC)	Indirect land use change occurs when land for an existing activity (e.g. food production) is converted to grow bioenergy feedstock which results in the relocation of that displaced activity to another area that is converted
iLUC emissions	The net change in greenhouse gas emissions from the soil and vegetation as a result of indirect land use change
Land Use Constraints	Constraints on the land available for bioenergy production. In the ELUM project we used the land constraints developed during UKERC's Spatial Mapping Project. See "Lovett et al. (2014), The availability of land for perennial energy crops in Great Britain. GCB Bioenergy, 6, 99-107"
Negative emissions	This denotes a net removal of carbon from the atmosphere, normally though the combination of biomass and CCS
Net Ecosystem Exchange (NEE)	In the context of the ELUM project it is a measure of the net exchange of gases (such as CO_2) between the atmosphere and the plant biomass & soil
Net Soil GHG emissions	Net soil GHG emissions denotes the sum of two changes: i) the increase or decrease in soil carbon stocks and ii) reductions or increases in soil GHG fluxes. In ELUM modelling, soil carbon is inversely equivalent to soil CO_2 emissions to air
Paired site comparisons	The process of comparing the GHG emissions and changes in soil carbon of a Control Site with a site which had been converted to bioenergy
Soil (Organic) Carbon (SOC) Stocks	Total amounts of carbon captured and retained in soils, arising from decomposing organic matter such as leaves and root tissues, and which can accumulate over many years
Starting soil carbon	The levels of soil carbon at the point of land used change
Transportation emissions	Emissions associated with different modes of transport such as trucks, rail, shipping, used to move biomass feedstock, or intermediate vectors such as wood pellets, along the supply chain

Appendix

APPENDIX TABLE A1

High level summary of the ELUM project findings by work package

	Ecosystem Services (literature review)	ELUM Fieldwork (soil carbon, soil GHG fluxes, 13C pulse-chase labelling)	Modelling: ECOSSE & ELUM meta-model
Overall transition results	» Arable to 1G – 'null transition' » Grass or Forest to 1G – net sources of soil carbon and N_2O due to increased fertiliser and disturbance » Significant knowledge gap in transitions to 2G bioenergy, especially for soil carbon changes below 30cm » 2G bioenergy can deliver benefits to ecosystem services in arable and some grassland transitions	» Soil carbon losses more likely to occur in soils with an initial carbon stock rich in soil organic carbon » Arable to 2G bioenergy crops saw gains in soil carbon and reductions in soil N_2O emissions » Grassland to 2G saw slight losses in soil carbon at 0-30cm level, no significant changes at deeper level » Management practices (harrowing, herbicides, fertiliser) can influence scale of impacts	» Soil carbon changes dominant factor in changes to net soil GHG (GWP) for 2G bioenergy » N_2O emissions small; CH_4 emissions negligible for 2G » Grass or Forest to 1G predicted to have significant N_2O emissions and soil carbon losses
Arable to 2G bioenergy (Miscanthus, SRC-W, SRF)	» Significant benefits may arise for a number of ecosystem services, including hazard regulation, disease and pest control, and both soil and water quality » Potential issues with Miscanthus and SRC for water availability where resources are scarce in arable areas	» Mean gains of soil carbon across ELUM sites where to 2G bioenergy crops[54] » Soil carbon gains seen in 0-30cm layer » Net decrease in soil N_2O emissions after transition » Lowest average starting soil carbon / ha^{-1}	» Significant soil carbon accumulation (relative to continued arable use) over most of UK, over 40 years » SRF > Miscanthus > SRC-W in terms of GWP reduction potential
Grassland to 2G bioenergy (Miscanthus, SRC-W, SRF)	» Most variable – and limited data » Lack of clarity about 'type' of grassland in studies reported » Benefits for some ecosystem services from grassland transitions (water and soil quality; hazard regulation), while remaining broadly neutral for others	Variable responses across ELUM sites: » On average, small losses of soil carbon were observed across most ELUM sites (at 0-30cm layer)[55]. Insignificant differences to control sites at 0-100cm level » Transitions to SRF, especially coniferous forestry, saw more soil carbon compared to control sites. Combined estimates of C stocks from different ecosystem components (e.g. soil and above-ground biomass) reinforced accumulation of carbon with coniferous SRF transitions	Most variable across UK: » Model based on soil carbon and soil GHG flux data from fieldwork, therefore 'GWP' doesn't take account of net biome productivity[56] – (harvested material is accounted for later in the whole value chain assessment) » Only transitions to SRF show some locations with a reduction in net GHG relative to grassland counterfactual » SRF > Miscanthus > SRC-W in terms of GWP reduction potential
Forest to 2G bioenergy	» Lack of data to confidently draw conclusions on impacts of transitions to 2G bioenergy crops	» Highest average starting soil carbon / ha^{-1}	» Transitions to 2G generally trigger net losses of soil carbon, with SRF predicted to produce smallest losses (relative to Miscanthus and SRC-W)

[54] Average changes in carbon stock measured across all ELUM arable sites: Miscanthus = 3.33+/-12.14 tC ha^{-1}; SRC = 9.69+/-13.42 tC ha^{-1}. See Rowe, R. et al. (2015) Initial soil C and land use history determine soil C sequestration under perennial bioenergy crops. GCB Bioenergy, in press.

[55] Average changes in carbon stock measured across all ELUM grassland sites: Miscanthus = -16.18+/-17.82 tC ha^{-1}; SRC = -30.28+/-10.96 tC ha^{-1}. See Rowe, R. et al. (2015) (as above).

[56] For a good description of the different terms and methods for assessing carbon budgets, the reader is referred to Smith, P. et al. (2010) "Measurements necessary for assessing the net ecosystem carbon budget of croplands". Agriculture, Ecosystems and Environment, 139, 302-315.

Appendix

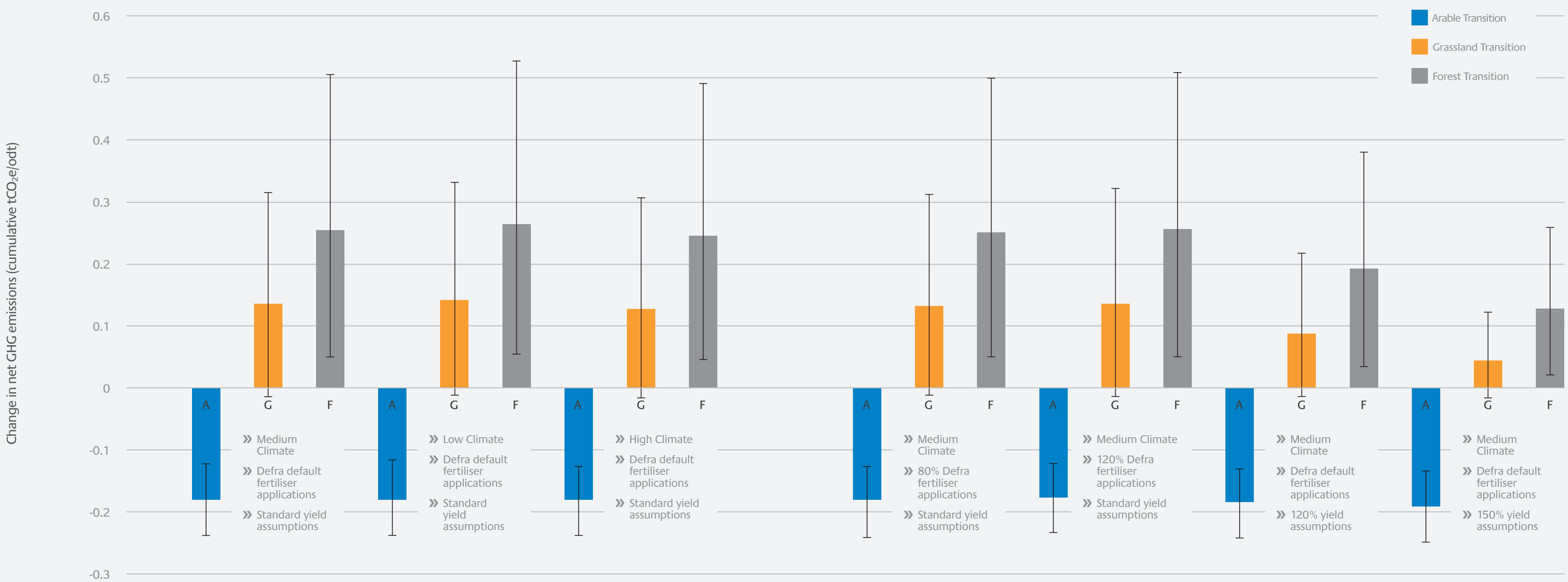
Continued »

APPENDIX FIGURE A1

Graph showing impact of climate, fertiliser and yield assumptions on the soil GHG emissions for Miscanthus transitions, over 40 years, expressed as tCO_2e/odt

Each group of three columns denotes a different scenario.

Figure A1 illustrates that yield has a larger impact on soil GHG emissions than climate or fertiliser inputs. Delivery of yield improvements through breeding programmes or agronomic management practices, could have an important and beneficial impact on lessening dLUC emissions.



Appendix

Continued »

An overview of some of the key findings from the ELUM project have been presented in this paper, but the reader is encouraged to refer to the many specific scientific journal publications listed below.

Key Papers directly from the ELUM project – WP1 (Literature Review):

» Harris, Z.M., McNamara, N.P., Rowe, R., Dondini, M., Finch, J., Perks, M., Morrison, J., Donnison, I., Farrar, K., Sohi, S., Ineson, P., Oxley, J.C., Smith, P. and Taylor, G. (2014) The ELUM project: Ecosystem Land Use Modelling and Soil Carbon GHG Flux Trial, Biofuels, 5, 111-116. http://dx.doi.org/10.4155/bfs.13.79

» Harris, Z.M., Spake, R. and Taylor, G. (2015) Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions, Biomass and Bioenergy, in press. http://dx.doi.org/10.1016/j.biombioe.2015.05.008

» Holland, R.A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D. and Taylor, G. (2015) A synthesis of the ecosystem services impact of second generation bioenergy crop production, Renewable and Sustainable Energy Reviews, 46, 30-40. http://dx.doi.org/10.1016/j.rser.2015.02.003

Key Papers directly from the ELUM project – WP2 (Fieldwork):

» Keith, A. M., Rowe, R., Parmar, K., Perks, M., Mackie, E., Dondini, M. and McNamara, N.P. (2015) Implications of land-use change to Short Rotation Forestry in Great Britain for soil and biomass carbon. Global Change Biology Bioenergy, 7, 541-552. http://dx.doi.org/10.1111/gcbb.12168

» Rowe, R.L., Keith, A.M., Elias, D., Dondini, M., Smith, P., Oxley, J. and McNamara, N.P. (2015) Initial soil C and land use history determine soil C sequestration under perennial bioenergy crops. Global Change Biology Bioenergy, in press. http://dx.doi.org/10.1111/gcbb.12311

» Parmar, K., Keith, A.M., Rowe, R.L., Sohi, S.P., Moeckel, C., Pereira, M.G. and McNamara, N.P. (2015) Bioenergy driven land use change impacts on soil greenhouse gas regulation under Short Rotation Forestry, Biomass and Bioenergy, in press. http://dx.doi.org/10.1016/j.biombioe.2015.05.028

Key Papers directly from the ELUM project – WP3 (Fieldwork):

» McCalmont, J.P., Hastings, A., McNamara, N.P., Richter, G.M., Robson, P., Donnison, I.S. and Clifton-Brown, J. (2015) Environmental Costs and Benefits of Growing Miscanthus for Bioenergy in the UK. Global Change Biology Bioenergy, in press. http://dx.doi.org/10.1111/gcbb.12294

» Harris, Z.M., Alberti, G., Jenkins, J.R., Rowe, R., McNamara, N.P. and Taylor, G. (2015) Land use change to bioenergy: identifying 'good' bioenergy options – land use change from grassland to SRC willow has an improved carbon balance, submitted.

Key Papers directly from the ELUM project – WP4 (Modelling):

» Dondini, M., Jones, E.O., Richards, M., Pogson, M., Rowe, R.L., Keith, A.M., Perks, M.P., McNamara, N.P., Smith, J.U. and Smith, P. (2015) Evaluation of the ECOSSE model for simulating soil carbon under short rotation forestry energy crops in Britain. Global Change Biology Bioenergy, 7, 527-540. http://dx.doi.org/10.1111/gcbb.12154

» Dondini, M., Richards, M., Pogson, M., Jones, E.O., Rowe, R.L., Keith, A.M., McNamara, N.P., Smith, J.U. and Smith, P. (2015) Evaluation of the ECOSSE model for simulating soil carbon under Miscanthus and short rotation coppice-willow crops in Britain. Global Change Biology Bioenergy, in press. http://dx.doi.org/10.1111/gcbb.12286

» Dondini, M., Richards, M., Pogson, M., McCalmont, J., Drewer, J., Marshall, R., Morrison, J., Yamulki, S., Harris, Z.M., Alberti, G., Siebicke, L., Taylor, G., Perks, M., Finch, J., McNamara, N.P., Smith, J.U. and Smith, P. (2015) Simulation of greenhouse gases following land-use change to bioenergy crops using the ECOSSE model. A comparison between site measurements and model predictions. Global Change Biology Bioenergy, in press. http://dx.doi.org/10.1111/gcbb.12298

» Pogson, M., Hastings, A. and Smith, P. (2012) Sensitivity of crop model predictions to entire meteorological and soil input datasets highlights vulnerability to drought. Environmental Modelling and Software, 29, 37-43. http://dx.doi.org/10.1016/j.envsoft.2011.10.008

Key Papers directly from the BVCM project:

» Samsatli, S., Samsatli, N. and Shah, N. (2015) BVCM: a comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – mathematical formulation. Applied Energy, 147, 131-160. http://dx.doi.org/10.1016/j.apenergy.2015.01.078

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