Programme Area: Bioenergy

Project: ELUM

Title: Executive Summary

Abstract:

The ELUM project was commissioned to provide greater understanding on the GHG and soil carbon changes arising as a result of direct land-use change (dLUC) to bioenergy crops, with a primary focus on the second-generation bioenergy crops Miscanthus, short rotation coppice (SRC) willow and short rotation forestry (SRF). The project was UK-bound, but with many outcomes which could be internationally relevant. Indirect land-use change impacts were out of scope. This 23 page report provides an executive summary of the ELUM programme of work including a description of the relationship between the fieldwork programme and the modelling and key outcomes.

Context:

The ELUM project has studied the impact of bioenergy crop land-use changes on soil carbon stocks and greenhouse gas emissions. It developed a model to quantitatively assess changes in levels of soil carbon, combined with the greenhouse gas flux which results from the conversion of land to bioenergy in the UK. The categorisation and mapping of these data using geographical information systems allows recommendations to be made on the most sustainable land use transition from a soil carbon and GHG perspective.

Some information and/or data points will have been superseded by later peer review, please refer to updated papers published via www.elum.ac.uk

ETI Project code: BI1001

Ecosystem Land-Use Modelling & Soil Carbon Flux Trial (ELUM)

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Project Executive Summary

REPORT

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1. Introduction and Context

Bioenergy has a key role to play in the UK's low carbon future including contributing to the UK's target to reduce its greenhouse gas (GHG) emissions by 80% (from the 1990 baseline) by 2050. It is one of the most complex, but also one of the most flexible renewable options: able to provide heat, power and both gaseous and liquid fuels. Both the DECC Bioenergy Strategy and the Committee on Climate Change's Bioenergy Review estimated that UK-produced bioenergy could provide around 10-12% of the UK's energy needs by 2050 and provide significant economic benefits.

Based upon the work of ETI and others, one of the key potential opportunities provided by bioenergy is the option to combine it with carbon capture and storage (CCS) to afford negative emissions. These negative emissions could be used to offset the need for expensive interventions elsewhere in the energy system, such as providing low-carbon fuels for use in aviation and shipping.

In choosing to use bioenergy, it is essential that the biomass feedstock is produced and used in a sustainable manner. Life Cycle Assessment (LCA) is often used to quantify the overall environmental impacts of products or services. In carrying out an LCA, all greenhouse gases (GHG) fluxes arising from the entire bioenergy supply chain are accounted for. Credits are given for uptake of GHGs, and debits for any positive GHG emissions, such as those associated with the transport or combustion of biomass.

Of increasing interest and concern when considering bioenergy is the impact of land-use change on GHG emissions and associated soil carbon stocks. GHGs include CO_2, CH_4 and N_2O and, along with changes in soil carbon (reflecting long term CO_2 fluxes), can result from direct or indirect land-use change. Direct land-use change (dLUC) accounts for GHG emissions and soil carbon stock changes associated with a change in land-use and management, from the pre-existing land-use to a bioenergy crop. Indirect land-use change (iLUC) concerns GHG emissions arising from additional land-use change elsewhere driven by displaced activity from the land converted to bioenergy production.

The ELUM project was commissioned to provide greater understanding on the GHG and soil carbon changes arising as a result of direct land-use change (dLUC) to bioenergy crops, with a primary focus on the second-generation bioenergy crops *Miscanthus*, short rotation coppice (SRC) willow and short rotation forestry (SRF). The project was UK-bound, but with many outcomes which could be internationally relevant. Indirect land-use change impacts were out of scope.

An outline of the ELUM project approach is given in Figure 1. The aim of the project was to develop a user-friendly modelling tool from which the impacts of bioenergy land-use change on soil carbon and field GHG balance could be explored spatially and temporally across the UK. The modelling tool outputs were derived from the well-established ECOSSE soil carbon and GHG model. An essential aspect of developing this model was the availability of data for model parameterisation and validation. At the start of the Project, the Project team established that there were extensive and critical data gaps around the availability of bioenergy crop field data and observations from across the UK and that existing crop yield models, such as

Miscanfor, ForestGrowth SRC and the Ecological Site Classification model (ESC)-Carbine were available for providing the required crop yield data. Experimental designs focused on obtaining UK-relevant bioenergy crop soil carbon data and GHG emissions data. In particular, the team implemented new 1 m deep soil coring techniques to provide bioenergy crop relevant soil carbon data (given their deeper root systems compared with more conventional crops). Other aspects of the work also included improving continuous GHG measurement technology and a review of ecosystem service provision under bioenergy.

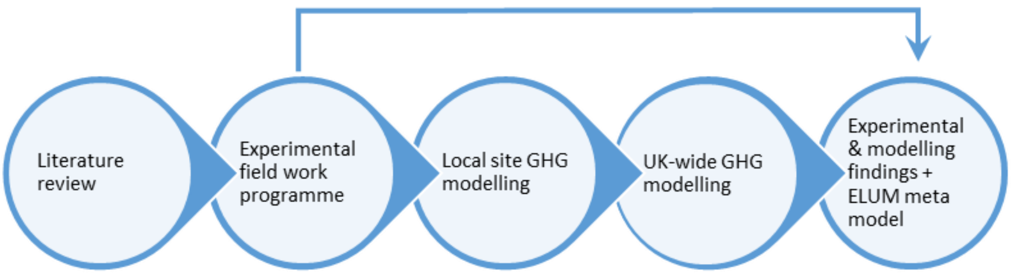

Figure 1: Outline of the ELUM Project Work Programme

2. Methodology

An early component of the ELUM project was a literature review on bioenergy-related soil carbon and GHG data for temperate climatic conditions. This demonstrated and confirmed that there were very little data available of direct relevance to commercial-scale, second-generation bioenergy in the UK. The primary focus for much of the work on second-generation bioenergy crops in the UK to date has been around yield and productivity, and as a result there have been a number of yield models developed in these areas. However, very little comparable work has been done on these crops with regard to their impacts on soil carbon and GHG balances. The programme of field work focused on these areas in order to have the greatest impact on reducing uncertainty in data inputs to the modelling work.

Experimental fieldwork on *Miscanthus*, SRC Willow, and SRF– and adjacent control sites – at locations across the length and breadth of mainland GB was conducted to capture data across both temporal and spatial scales. In total, 70 field sites were visited on a one-off basis to give high spatial-resolution soil carbon data, together with four routinely-visited network field sites across the UK which were instrumented to give high-resolution temporal GHG data (Figure 2). A range of different instruments and techniques were used to capture the key information and data for model validation and testing at these network field sites.

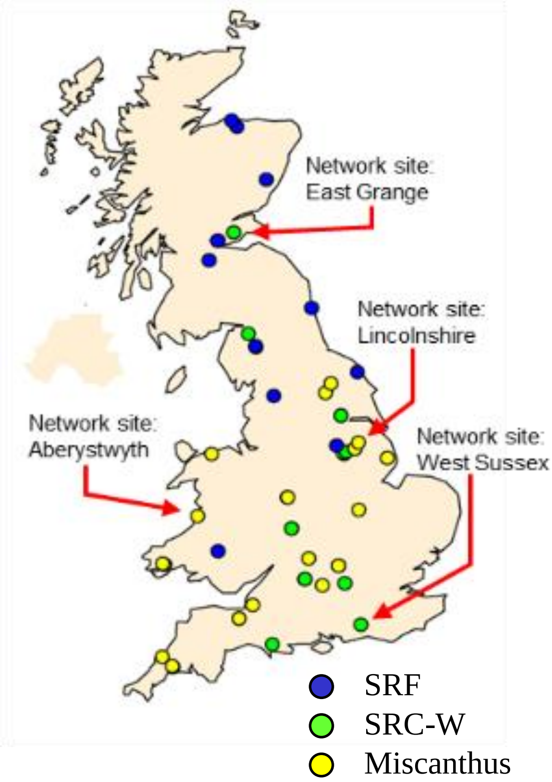

Figure 2: Spatial Distribution of the ELUM Field Sites

The measured data were then used to test site-specific (local) modelling outputs of the impacts of land-use change on soil carbon and GHG. Using the range of measured data, the predictive capacity of the underlying soil process model was refined and improved. By combining the improved soil process model with pre-existing bioenergy yield models and spatially explicit maps of soils and climate for the UK, it was possible to simulate soil carbon and GHG changes from bioenergy land-use change across the UK through to 2050.

The outputs from the detailed ECOSSE process-based model were then extracted to compile a user-friendly meta-model which provides spatially explicit, high-resolution information on the impacts of land-use change for bioenergy in the UK.

3. Literature Review

To validate the Project Team's understanding of the gaps in knowledge on UK second-generation bioenergy crop soil carbon and GHG emissions data, a literature review was carried out. This literature review confirmed this data deficiency. However, where such information did exist, they were primarily based on modelling work, rather than empirical, measured data, and generally were not obtained from commercial-scale and commercially-operated sites. The second-stage literature review carried out towards the end of the Project in 2013 revealed an increase in the volume of empirical data as more researchers start to explore this knowledge gap on second-generation bioenergy crop land-use change internationally.

Despite the limited data available in both the academic and grey literature, it was possible to conclude from the review that more work was required to enhance the data available, in particular, in the following areas:

- Soil carbon stock assessments - especially below the standard 30 cm depth
- GHG emissions from both soil and crops
- Commercial-scale bioenergy crops in the UK

A review was also undertaken on the impacts of land-use change to bioenergy on Ecosystem Services (ES) in the UK. Once again, this demonstrated a lack of relevant literature information, and that where such information was available, it was more prevalent for first-generation crops such as wheat and sugar beet rather than the second-generation crops of more interest to this project. Despite the limited data, this review suggested that transitions from first-generation bioenergy crops to second-generation bioenergy crops were generally beneficial for ES whilst transitions from grasslands to second-generation bioenergy crops were typically less beneficial than transitions from cropland.

4. Fieldwork Program

Based on pre-existing knowledge, and supported by the literature review, a programme of fieldwork was designed to help reduce uncertainties related to changes in soil carbon and GHG fluxes caused by land-use change to second generation bioenergy crops. This fieldwork was designed in collaboration with the modelling team on the Project, so that it would best meet the requirements for parameterisation and testing of the underlying soil process model (ECOSSE). As noted above, existing yield models provided additional inputs.

The key features of the experimental design were as follows:

1. Given there were no available data on soil carbon levels to the standard 30 cm depth for second-generation bioenergy crops in the UK (and that these crops have deep roots), a process for sampling soils down to 1 m depth was designed and implemented.
2. Given the very limited data on GHG emissions from UK soils growing bioenergy crops, both spatial scale and temporal scale measurements were required.
3. To improve approaches to GHG emission measurement using high-resolution and high-frequency methodologies.

The experimental program was designed to support the development of the model. As such, the field sites selected for measurement were varied to enable model improvement and testing at as wide a range of extremes as possible. Aside from accessibility and available land management information, other key requirements for these sites are shown in Table 1.

Table 1: Key Characteristics of ELUM Field sites

Key Features of Selected ELUM Field Sites
• Focus on range of bioenergy crops (*Miscanthus*, SRF, SRC)
• Balance of starting land uses (grass, arable)
• Climate differences
• UK spatial distribution
• Variety of soil types
• Mixed age crops
• Commercial-scale
• Co-located control site

Once identified, these sites were then subject to one or two possible measurement approaches within the project, as follows:

- **Static approach** where soil core samples were taken for carbon stock determinations from a single visit to each site.
- **Dynamic approach** where GHG emissions data were collected at a smaller number of well-instrumented field sites visited on a regular basis throughout the project

The soil core sampling programme was designed with Consortium input, but completed by a single CEH team. Where a range of different partners were undertaking experimental work, common methodologies and approaches were agreed between project staff across the Consortium. This was of key importance to ensure the highest levels of consistency and reproducibility of measurements across the field sites. These sampling and measurement techniques are a key output of ELUM, and have been referred to and used by other researchers in follow-on projects. The different types of measurement and analyses undertaken at these two types of site and the value to the project are expanded in further detail in Table 2.

Table 2: Measurement Approaches in ELUM

	Static Approach: Single Visit Sites	**Dynamic Approach: Multiple Visit Sites**
Site Objectives	Measurements over wide geographic area (high spatial variability)	Repeat measurements over 2 years (high temporal variability)
Measurement frequency	Low (one visit per site only)	High (hourly to monthly, depending on instrument)
Number of sites	70	4 (comprising 11 fields)
Types of Measurement	Soil carbon (30 cm & 1 m), leaf litter	GHG (CO_2, CH_4, N_2O), soil carbon, leaf litter
Management Information	Yield statistics, basic historic crop management information for model	Yield statistics, detailed crop management information for study period.
Additional Information	-	Novel GHG experiments
Value to model	Validating Soil Carbon	Validating GHG emissions

4.1. Soil Carbon

The soil carbon work was undertaken at static, single-visit sites across the UK. In line with specific modelling requirements, a series of 70 sites across the UK were identified that met the species type, geographical, climatic and other characteristics required (Table 1). A paired-site approach was adopted, whereby two fields were sampled at each site, the pre-existing bioenergy crop and a nearby control field (representing the original/pre-existing land use). Statistically-designed sampling of soil carbon was conducted down to two depths, 30 cm and 1 m for both the bioenergy and control fields. Coupled with landowner knowledge of the period since transition to bioenergy crop and analyses of the soil carbon levels, it was possible to compare the bioenergy crop soil carbon with the unchanged, control site.

Initially, the work was on 30 cm soil coring, with a small amount of 1 m coring undertaken at the static sites. However after data interpretation of the early work, the enhanced value of the soil carbon results down to 1 m meant that soil coring was latterly focused exclusively on the 1 m depth. This is important, because the greater rooting-depth of many second-generation crops means they have more capacity to affect soil carbon at depths below 30 cm.

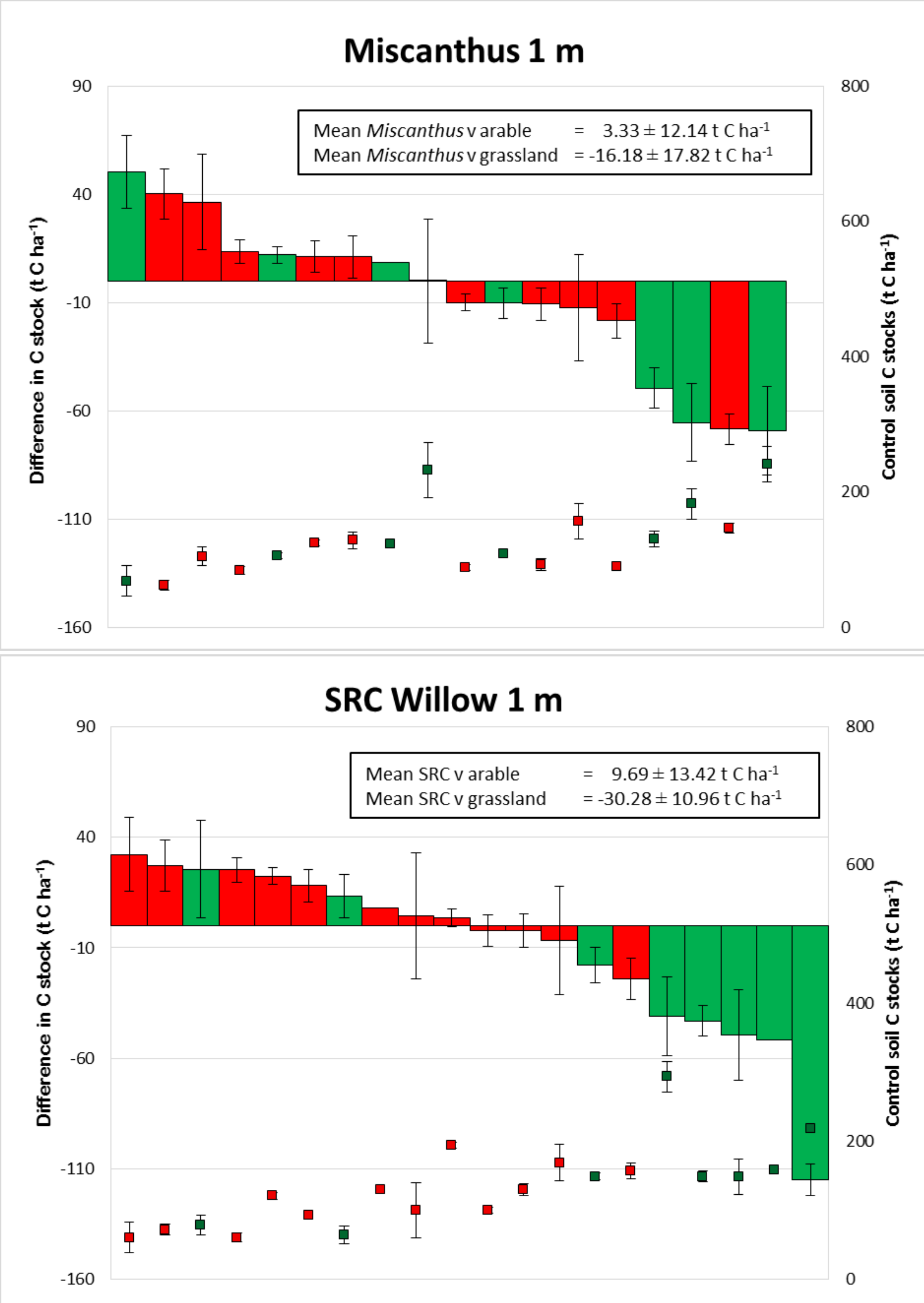

Figure 3: Difference in soil carbon stocks between the control reference site and the bioenergy crops (bars). Positive values (above the zero line) indicate a higher soil carbon in the bioenergy crop than in the control fields, bars below the line a lower soil carbon stock. Points and right hand axis show the control soil carbon stocks. Green bars indicate grassland transitions, red bars indicate arable transitions. Error bars represent: pooled standard deviation (SD) of difference from control site (bars); SD for the control site C stock (square dots).

When assessed down to 1 m, there were no significant statistical differences in soil carbon when transitioning to either SRC willow or Miscanthus from either arable or grassland. In contrast, transitions from grassland to either SRC or *Miscanthus* led to reduction in soil C in surface 0-30 cm, highlighting the importance of a deeper assessment of the soil carbon stock. However, fewer 1 m cores (3) were taken compared to the 30 cm cores (9), potentially resulting in reduced statistical power to detect impacts at greater depth. At a site-specific level, it was generally observed that transitions from arable were more likely to be favourable than those from grasslands (Figure 3). Overall, our analyses showed that the dominant factors of influence were the original land-use history and the initial carbon stock prior to the land-use change (Figure 3).

For SRF transitions, this work demonstrated that in general, coniferous forestry tends to show greater levels of soil carbon compared to the control sites, which were nearly all upland grasslands. For broadleaved species of SRF, there were no statistical differences in soil carbon, but the greater variability suggested species type and location are key determinants. Whilst transitions to Eucalypt species were negative for soil carbon, these results are based on only a few young sites, and impacts may change over time. We therefore only have limited confidence in our ability to make longer term predictions for these species. For SRF transitions the initial soil carbon stocks did not explain the changes in the SRF carbon stocks (Figure 4).

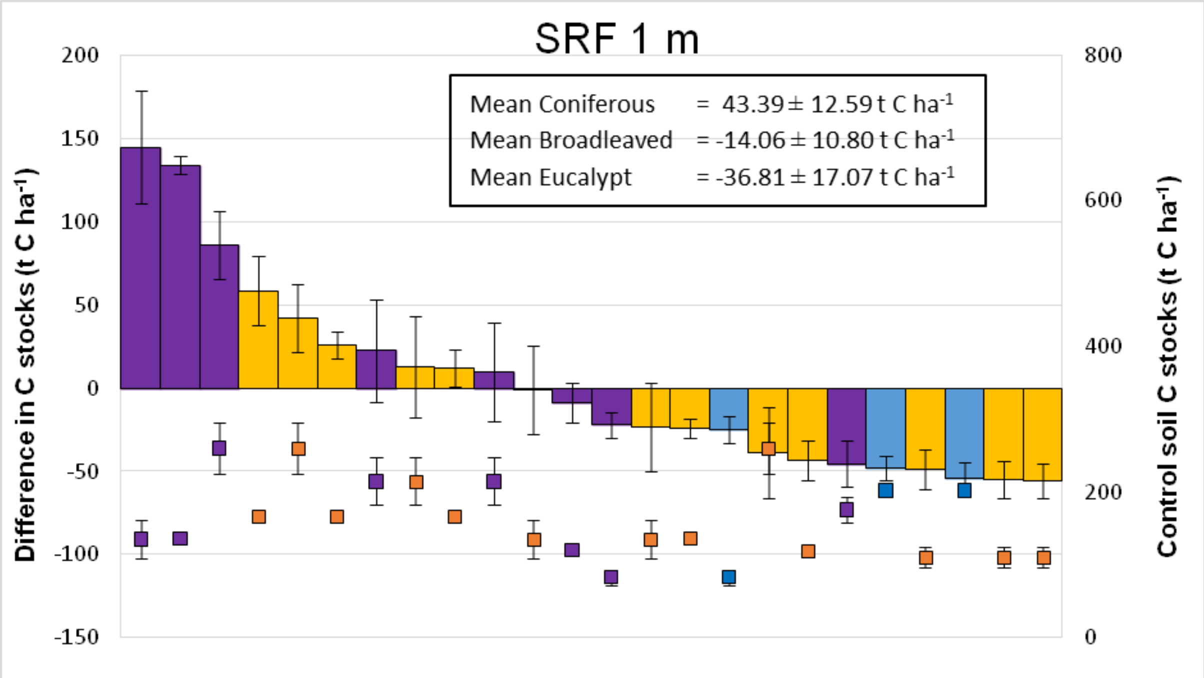

Figure 4: Difference in soil carbon stocks between the control reference site (primarily grassland) and the bioenergy crops (bars). Positive values (above the zero line) indicate a higher soil carbon in the bioenergy crop than in the control fields, bars below the line a lower soil carbon stock. Points and right hand axis show the control soil carbon stocks. Purple bars indicate transitions into coniferous, yellow into broadleaf and blue into Eucalypt. Error bars represent: pooled standard deviation (SD) of difference from control site (bars); SD for the control site C stock (square dots).

4.2. GHG Measurements

The measurement work at the dynamic sites was undertaken over a two-year period. For some pre-existing sites, data existed prior to the start of the ELUM project, and this has been used to further enhance the data available for modelling work.

Two GHG measurement technologies were used: Eddy Covariance (EC) and Chamber measurements, as shown in Figure 5.

Eddy Covariance (EC)

Eddy Covariance provides automated, high-frequency CO_2 data by using an infra-red gas analyser, coupled with an anemometer, to monitor the CO_2 emanating from an area of land ("the fetch"). The raw data requires significant processing and is sensitive to wind speed and direction, and rainfall. Eddy Covariance has the advantage of measuring the CO_2 flux over large areas of growing vegetation.

Chamber Techniques

Chamber measurements rely upon the enclosure of a small area within a gas-tight chamber. The gas is sampled and measured by a portable gas analyser, or can be taken back to a laboratory for analysis. This technique is low-frequency, but has the advantage that it can analyse for CO_2, N_2O and CH_4. Chambers cannot easily be used to monitor growing vegetation.

Figure 5: The two principal GHG detection systems within ELUM

The two measurement systems both have different characteristics for monitoring GHGs over field sites, and these are outlined below (Table 3).

Table 3: The contrasting characteristics of the Eddy Covariance and Chamber system for GHG monitoring

Eddy Covariance (EC)	Chamber
High frequency	Low frequency (once/month)
Dependent upon wind direction	Independent of weather
Unattended operation	Manual operation
Typically measures just CO_2	Sampling of CO_2, N_2O & CH_4

A key finding from the GHG measurement at the dynamic network sites was that the majority of the bioenergy crops were net sinks for CO_2, with the exception of Aberystwyth *Miscanthus* in the first year of planting (after land-use change). This means that more CO_2 was being fixed into biomass, with a proportion entering soil, than was emitted to the atmosphere through plant and soil respiration (Table 4). At this same Aberystwyth site, N_2O and CH_4 emissions were also much higher than for any of the other field sites, and this may in part also be associated with the land-use change. For all other sites, N_2O emissions were negligible compared to the rates of CO_2 exchange, and CH_4 emissions were lower still and thus inconsequential. At East Grange, SRF Scots Pine bare root stock was planted amongst the existing grassland. This lack of disturbance of the existing grassland potentially helped maintain the observed high carbon uptake values. At East Sussex SRC willow results in carbon uptake whilst the adjacent grassland was a net source of carbon.

Table 4: Summary of the annual GHG balances of land cover types at the field sites. Fluxes reported for N_2O and CH_4 are the mean ± 1 standard error based upon chamber replication. N_2O and CH_4 fluxes are expressed on a CO_2 equivalent basis. Negative fluxes indicate that the system is a sink, and has on balance removed GHG from the atmosphere and into the biomass.

Field site	Land cover and year of sampling	NEE ($g\ CO_2\ m^{-2}$)	N_2O ($g\ CO_2\ eq\ m^{-2}$)	CH_4 ($g\ CO_2\ eq\ m^{-2}$)
Aberystwyth	Miscanthus 2012	968	710 ± 120	112 ± 103
	Miscanthus 2013	-440	234 ± 57.3	11.1 ± 14.4
East Grange	SRF 2012	-3828	7.01 ± 0.46	-0.58 ± 0.13
Lincolnshire	Miscanthus 2012	-1771	0.02 ± 0.57	0.16 ± 0.28
	SRC willow 2012	-1588	4.96 ± 3.63	-0.58 ± 0.69
	winter wheat	-2439*	31.8 ± 5.35	-0.67 ± 0.35
	spring barley	-906**	42.2 ± 7.47	4.11 ± 3.32
West Sussex	SRC willow 2013	-3234	14.5 ± 2.51	-2.04 ± 0.38
	grass 2013	862	22.99 ± 6.74	1.16 ± 1.62

Asterisk indicates crops for which full year of NEE was not available. In each case NEE presented is the emission balance for * 5 April – 8 August 2012 and ** 25 May – 1 September 2013.

4.3. Methodologies and Technologies

In addition to using existing technologies, new measurement techniques – Skybeam and ^{13}C Stable Isotopic Pulse-Chase Monitoring – have been developed and used to improve the assessment and understanding of GHG emissions from plants and soil.

Skybeam is an automated system which combines some of the advantages of chamber measurements (insensitive to rain, multiple gas analytical capability) with the higher frequency of measurement more typically associated with Eddy Covariance (Table 3). This enables real-time, high-frequency gas monitoring, over growing plants across a set of closely located sites (Figure 6). Using Skybeam, this high-frequency measurement technique demonstrated that N_2O emissions were highly variable in both space and time over *Miscanthus*, which the low-frequency traditional chamber techniques were unable to capture (Figure 6).

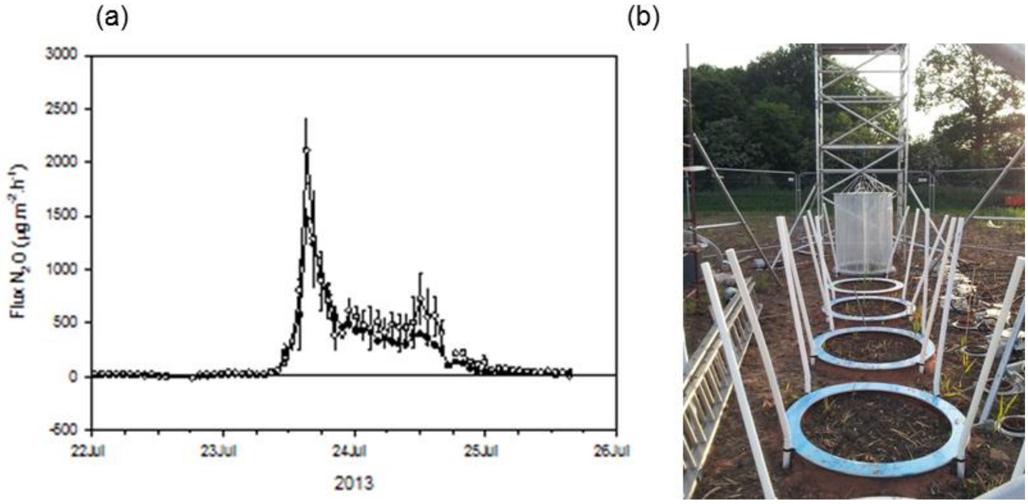

Figure 6: SkyBeam: Figure (a) shows N_2O measurement of the Miscanthus; Figure (b) shows the general SkyBeam set-up

Skybeam was only deployed at the Lincolnshire field site. It was found to be too expensive and too complex to operate to be able to use at other ELUM network field sites.

Stable Isotopic Pulse-Chase methods were developed and used to explore carbon assimilation and retention pathways in bioenergy crops. This comprised extensive fieldwork at two of the dynamic network sites, whereby $^{13}CO_2$ was introduced into tented enclosures containing stands of either *Miscanthus* or SRC willow crops. Whilst the results from this work did not feed directly into the modelling, they provided additional context to help understand some of the observations at these sites which were fed into the modelling work. For example, the pulse labelling revealed a greater retention of fixed $^{13}CO_2$ in the plant biomass for Miscanthus compared to SRC willow, generally supporting the results shown in Table 4 for the Lincolnshire site.

5. Modelling

The spatial modelling component of ELUM is the final Project output and distils the range of site-specific measurements and modelling activities into forward predictions of the impacts of land-use change to bioenergy crops on GHG balances. This has resulted in the further development of an existing process-based model (ECOSSE), driven by outputs from a number of bioenergy crop yield models, to give a process model capable of predicting changes in soil carbon and GHGs emissions for the whole UK from 2015 to 2050 at 1 km^2 resolution. The operation and interpretation of such detailed process models is complex and requires significant computing power. Hence, the stand-alone ELUM meta-model has been developed to allow users to obtain estimates of changes in GHG and soil carbon stock in a quick and user-friendly manner (Figure 7). The meta-model is based upon a look-up table of all spatial outputs from the detailed process models, and will eventually be downloadable from CEH *via* the ELUM website.

Before building the over-arching process model and meta-model, it was necessary to validate model predictions against measured data. This was achieved by using 50% of the measured soil carbon and GHG fluxes to refine existing model outputs, and the remainder to independently validate these improved models. The refinement and validation of the model to simulate soil carbon was carried out for a selected range (70) of sites across the UK. The validation process was essential to apply the model widely across UK, and temporally to 2050, with a high degree of confidence on the model efficiency. This wider spatial extrapolation was underpinned by the use of existing soil map data for the UK (Harmonized World Soil Database), after checking that the Harmonised World Soil Database gave similar model outputs to those using measured soil characteristics as input to the model.

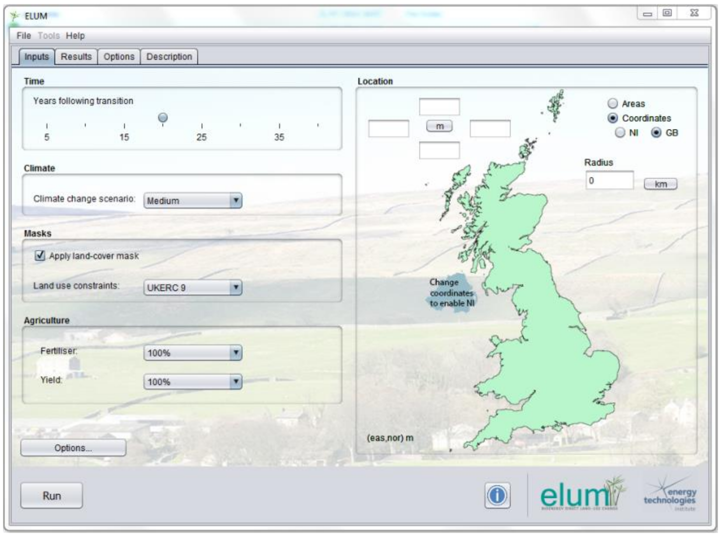

Figure 7: The Graphical User Interface (GUI) of the ELUM Meta-model

5.1 Site-Specific Modelling

The site-specific modelling showed that the ECOSSE model was extremely accurate in predicting soil carbon for land-use change from conventional crops (arable and grassland) to Willow, Miscanthus and short-rotation forestry, to a soil depth of 1 m (Table 5). This is of critical importance as a major outcome of ELUM research is that changes in soil carbon dominate the overall likely impact of dLUC on global warming potential (GWP), and thus underpins the importance of sampling down to 1 m. The experimental sites covered a wide range of soil characteristics and meteorological conditions (as shown in Table 1), hence, providing a good representation of the variety of conditions that occur in the UK.

Table 5: Correlation of Process Model with Soil Carbon at two Depths. Values for *R* range from -1 to +1, with -1 indicating a negative correlation, 0 indicating no correlation, and +1 indicating a positive correlation.

	SRF	Miscanthus	Willow
R = Correlation Coefficient Soil carbon (0-30 cm)	0.93	0.94	0.74
R = Correlation Coefficient Soil carbon (0-1 m)	0.87	0.93	0.90

At the site level, there were good correlations between each measured GHG flux and the modelled values. Results for soil CO_2 emissions (i.e. loss of C from the soil as CO_2) from bioenergy and conventional crops, measured using three different techniques, all showed good correlations with the modelled values, with an average correlation coefficient of 0.6 across sites and measurement types. Correlation coefficients for N_2O and CH_4 ranged from 0.05 to 0.61. Although these correlations were lower than for soil carbon stocks and CO_2 emissions, the model outputs were still within experimental error. It should be noted that the overall level of these two global warming gases, even allowing for their higher global warming potentials, was still very much lower than for soil carbon – CO_2 emissions are the dominant influence on land-use change greenhouse gas balance.

For all bioenergy crops evaluated in ELUM, the importance of sampling soil carbon to 1 m depth was demonstrated where such deeper rooted crops are involved. If only shallower depths were considered, then this had a significant impact on the modelling outcomes.

5.2 UK-wide Spatial Modelling and the Meta-Model

Significant computing resources are required for the ECOSSE UK-wide spatial simulations. Using a 1 km grid, there are nearly 0.25 million grid cells in the UK, and each cell may contain up to 5 different estimated soil types, each of which must be simulated. With 18 possible land-use transitions, and 3 ‘null’ transitions, this results in over 5 million simulations to run, neglecting multiple soil types in each grid cell. ELUM results were obtained using three different climate scenarios, bringing the number of simulations to around 30 million, and over 100 million when all soil types are considered. Further to this, results for different management and yield improvements have been also considered and the model is run for up to 35 years up to 2050.

When moving from the site-specific local modelling level to the UK-wide spatial modelling level, site-specific measured data on soil carbon are substituted with data derived from soil databases (Figure 7). The soil databases were re-projected to provide information on a 1 km^2 grid square comprising the five dominant soil types, an area-weighted average of which is an input to the model. Inevitably, this approximating of soil types will give rise to uncertainty in the resulting model outputs, but when this uncertainty was quantified, it was found to be quite small (R = 0.79), suggesting that in general, these databases provide reliable inputs to the model across the whole of the UK.

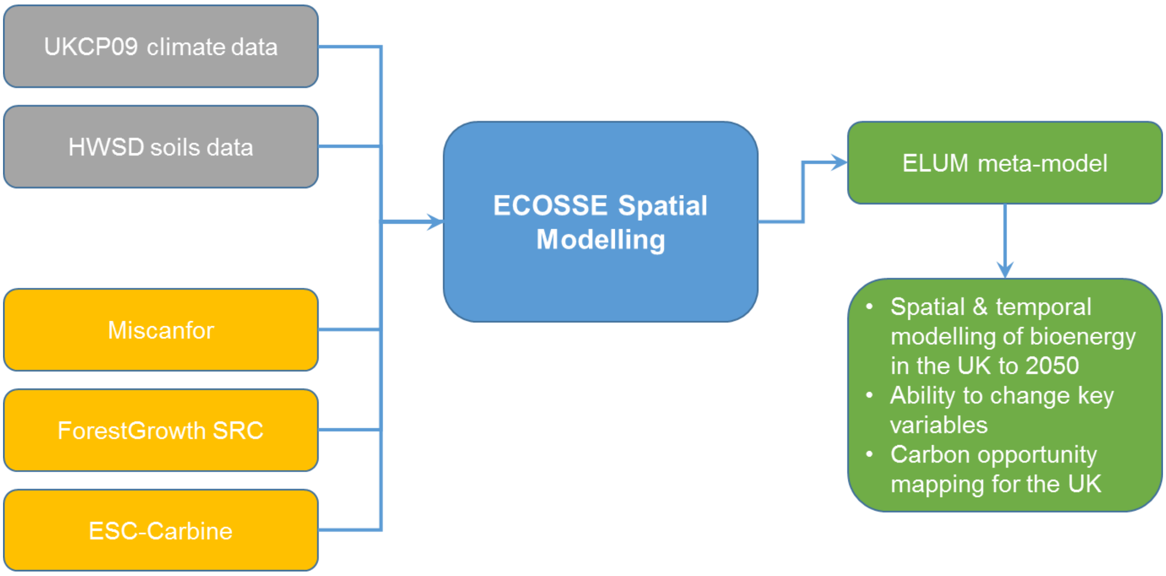

Figure 8: Flow of inputs and key modelling outputs

The crop yield projections are based on models that are parameterised and calibrated for existing cultivars and current management practices. In the case of SRF, high yielding SRF-Poplar was chosen for the simulations. In the future however, crop breeding and improvements in management practices will likely lead to increases in crop yield over time. In addition, the yield models do not consider the impact of pests and disease. Climate variability and changes in the frequency and severity of extreme events can have significant, non-linear impacts on crop yields because crops exhibit threshold responses to stress factors. Therefore, the lack of short-term climate variation in the climate projections used in this work presents a potentially large source of uncertainty in the predicted yields and, since yield is a key driver of ECOSSE, subsequently the estimated bioenergy GHG balances.

As noted above, a more usable meta model has been derived from the ECOSSE model. The meta model uses look up tables derived from the ECOSSE model to provide its outputs, based on the following broad variables:

- Selection of area(s) of interest up to and including the whole of the UK (at 1 km^2 resolution)
- Time periods up to the year 2050
- Different climate change scenarios
- Different fertilisation and yield scenarios
- 18 different land-use transitions
- 5 GHG-related output measures (including soil carbon and GHGs)

Results from the meta-model can be viewed in the GUI or exported for a range of uses. An example of how exported meta model results can be presented is shown in Figure 9.

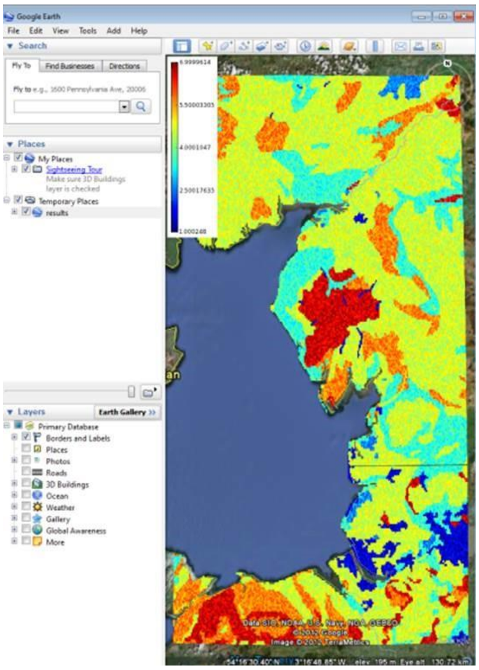

Figure 9: ELUM Meta-model Results Exported to Google Earth ®

5.3 Modelling Outcomes - Effects on Net Global Warming Potential

The outcomes from the modelling can be summarised through reporting the net GHG balance for a given transition. This is calculated as the sum of changes in N_2O and CH_4 emissions, minus the change in soil carbon, all expressed as CO_2 equivalents using 100 year global warming potential values (in this calculation, CO_2 emissions are accounted for by the change in soil C). A positive net GHG balance represents an emission to the atmosphere and represents detrimental change at the field level[1]; a negative net GHG balance represents a removal from the atmosphere and is beneficial at the field level. However, it is important that these results are taken in the wider life-cycle context of bioenergy. These include other whole system GHG emissions; for example, those saved when bioenergy substitutes fossil fuel in energy generation. The impact of soil GHG balance is largely dominated by effects on soil carbon with the difference among *Miscanthus*, SRC and SRF largely determined by yield, since higher yields mean higher carbon returns to the soil, which increases soil carbon stocks relative to lower yielding bioenergy species.

Simulating for the UK, the mean, minimum and maximum changes in net GHG balance from 2015 to 2050 following LUC from arable crops, grass and forest are shown in Figure 10. This modelling indicates that SRF offers the best bioenergy opportunities (in terms of changes in net GHG balance at the field level) and is the only bioenergy crop to provide potentially beneficial impacts on field level GHG balance when planted on grassland sites. The beneficial effects following conversion of grassland to SRF are perhaps surprising, given that land-use

[1] A full life cycle assessment is needed to test whether the impact of land-use change is overall negative or overall positive at the system level. A detrimental change at the field level may, when considered at the full system level, still result in an overall positive system impact.

changes from grassland generally lead to an observed loss of soil carbon (Figure 10). The beneficial global warming potentials under the grass to SRF transition are small in comparison to the conversion of arable crops to *Miscanthus*, SRC and SRF. Overall, forested land provides the least-favourable opportunities for bioenergy for all transitions with detrimental effects on net GHG balance at the field level as might be expected.

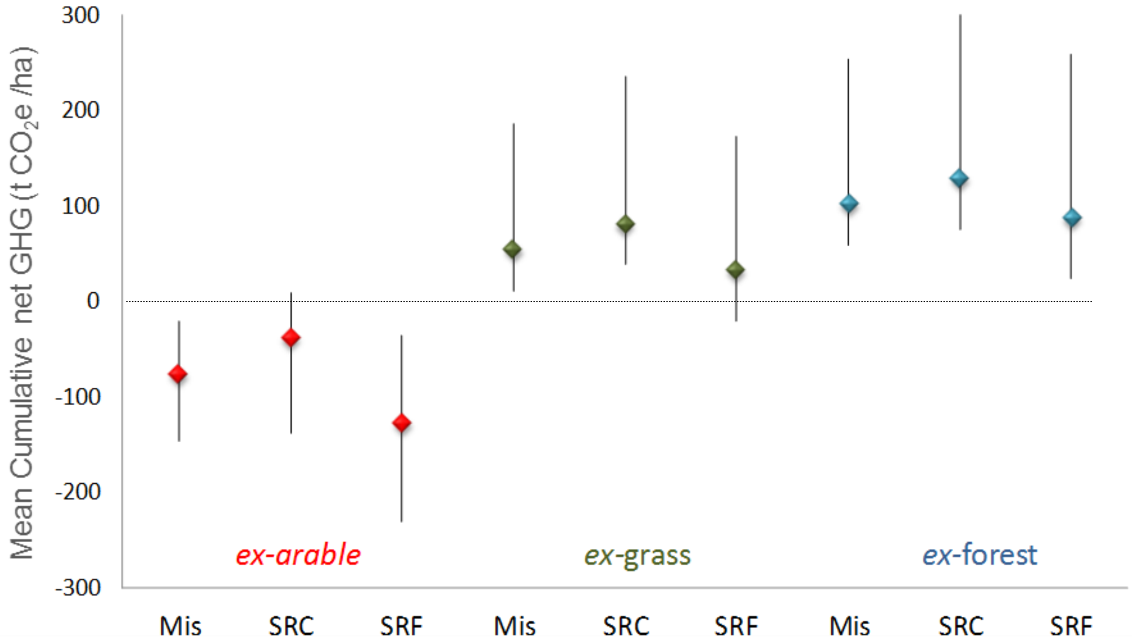

Figure 10: Mean impacts on net GHG emissions from 2015-2050 of bioenergy transitions under the medium climate scenario, as modelled for all suitable areas in mainland GB. Points mark mean values with individual lines representing the minimum – maximum range. Points above zero indicate a detrimental effect on net GHG balance; points below a positive effect.

6. Discussion

The ELUM project was commissioned to develop a modelling framework to quantitatively assess changes in the levels of carbon in soil, combined with the GHG flux which results from the conversion of land to bioenergy crop production in the UK. These field GHG emissions are widely regarded as having the greatest uncertainty for the GHG life-cycle balance across the whole bioenergy supply chain.

The collective findings of this work suggest that bioenergy crops are expected to have a largely negligible impact on emissions of non-CO_2 GHGs, with small potential benefits with regard to N_2O emissions for transitions from arable to bioenergy. Therefore, changes in soil carbon dominate the overall soil GHG balance for a given transition. ELUM field data showed no significant difference in soil carbon at 1 m depth from grass or arable. However, taking more core samples would improve the statistical power to detect impacts at greater depth. Other work regarding grassland to SRC suggests that soil carbon losses in topsoil are offset by increases lower in the soil profile, resulting in no significant changes in soil carbon stocks. On a site by site basis, the establishment of SRC willow and *Miscanthus* on arable fields appear to be more favourable to establishment on grassland, however, this was not always the case (Figure 3). Closer examination of ELUM field data showed that another important factor of influence was the initial pre-conversion soil carbon stock, with lower initial stocks leading to a greater likelihood of post conversion (to bioenergy crop) gains. As soils under grasslands (153 ± 66 t C ha^{-1}, this study) typically hold more carbon than arable (112 ± 40 t C ha^{-1}, this study) this helps explain our observed result. For our modelling, we chose to simulate permanent pasture which dominates UK agricultural grasslands. These grasslands have higher associated soil carbon values than those of rotational grasslands which are more similar to arable crops.

Our modelling results matched the trends observed in the measurements for *Miscanthus* and SRC willow. For our measurements, transitions from arable into *Miscanthus* and SRC, a small but statistically insignificant increase in soil carbon stocks was found. The model, which projects 35 years forward, and beyond our range of measurements, suggests further soil carbon accumulation and an improved net GHG balance may occur. Conversely, a small but statistically insignificant loss of soil carbon was measured under transitions from grassland to *Miscanthus* and SRC. On a crudely annualised basis, and taking account of the full GHG impact (from Figure 10), this corresponds to an average rate of carbon loss from the soil of 0.4 and 0.6 t C ha^{-1} y^{-1} for *Miscanthus* and SRC, respectively.

Based on measurements, transitions to coniferous SRF species were found to be the most positive in terms of impacts on soil carbon, with higher soil carbon found compared to the control using both 30 cm and 1 m sampling approaches (Figure 4). Broadleaved tree species were found to have neutral effects on soil carbon overall. Again results were consistent through the soil profiles using both 30 cm and 1 m sampling approaches. In the case of *Eucalyptus* species however, data was extremely limited, both in terms of the number of transitions (4) and the range of transition ages available (6-8 years). This limitation reflected the current status of *Eucalyptus* plantations in the UK as, despite our best efforts, these were the only suitable plantations identified for sampling. For our modelling, we chose to simulate

SRF Poplar which is a highly productive species which will lead to more optimistic estimates of soil carbon stocks compared to lower yielding varieties.

Across the GHG network sites, net carbon uptake was observed, meaning that fixation of CO_2 into plant biomass was greater than any losses of carbon through plant or soil respiration. Though we only monitored net carbon uptake in high resolution at a number of our sites (Table 4), this result was largely consistent across these sites. Given an average yield of 7-10 odt ha^{-1} yr^{-1} and a biomass carbon content of 45%, over a 35-year life span, bioenergy crops could sequester 110-157 t C ha^{-1} into above-ground biomass. This carbon in biomass represents a considerable fossil fuel offset which is likely to mitigate any LUC-induced soil carbon loss over this same time period. Providing an exact benefit of this biomass in terms of the soil GHG mitigation would require a full life-cycle analysis, and is beyond the scope of this project.

The crop yield projections used in ELUM are based on models that are parameterised and calibrated for existing cultivars and current management practices. Many emerging improved management processes and novel crop varieties have the potential to increase crop yields which would be expected to benefit soil carbon. Our modelling showed that yield increases of 20% and 50% did significantly benefit soil carbon. This magnitude of change was, however, insufficient to produce a mean positive benefit for forest and grassland transitions under a 50% yield-increase scenario. SRF and *Miscanthus* showed the greatest sensitivity to proportional changes in yield. Overall, these findings suggest that under higher-yielding scenarios, the broad conclusions inferred from the modelling results for soil carbon would remain the same. Any beneficial changes to yields would, however, improve the fossil fuel offset value of using biomass crops.

The ELUM project has created tools for exploring the implications of land-use change to bioenergy on soil carbon and GHG emissions. The major conclusion from this research is that changes in soil carbon stocks are the primary determinant of whether a given LUC is beneficial or negative in terms of a site net GHG balance. Recommendations arising from ELUM should be considered in combination with the above-ground biomass component and subsequent downstream processing and use for an overall lifecycle impact. Further, the valuation of additional ecosystem service impacts should be incorporated into sustainability assessments. This work does not cover these aspects in detail, but does fill the current and substantial knowledge gap regarding impacts on soil carbon stocks and GHG emissions. Going forward, this will enable a more accurate assessment of the full lifecycle impacts of these bioenergy crops.

7. Key Outcomes and Summary

The aim of the ELUM project was to develop a deeper understanding around the impacts of direct land-use change to bioenergy crops in the UK. The ELUM team has successfully delivered the Project, having set up a major experimentation programme which in turn has supported the development of the UK-wide spatial simulation model.

The meta model can be used by researchers to explore the GHG balance of a range of land-use transitions to grow bioenergy crops in any area in the UK, with climate change scenarios and yield improvement options. The ELUM protocols are proving to be valuable to other researchers in the field to develop data for comparison with that produced by ELUM. The ELUM datasets will be usable by modellers for a range of purposes, including full life-cycle assessments of bioenergy production.

The uncertainties in the model simulations are quantified and reported for all outputs. However, model users should be aware of the uncertainties arising from the use of current available datasets to drive the model (e.g. yield estimates and soil property databases).

An important aspect of the ELUM study is that its scope is restricted to the field level only. When taken in the overall system level context, a positive overall system GHG impact can potentially be achieved, even if there might be a detrimental field level impact. In such a case, management steps may need to be taken to ensure sustainability at the field level.

7.1 New Understandings on Land-use Change

A key finding shown by the ELUM project is that land-use change to bioenergy crops can lead to either positive or negative impacts on soil carbon and GHG emissions at the field level.

Changes in soil carbon stocks are the primary determinant of whether a given land-use change to a bioenergy crop is beneficial or negative in terms of a site net GHG balance (i.e. at the field level). By comparison, GHG fluxes of N_2O and CH_4 are orders of magnitude smaller in term of their contribution to the site net GHG balance.

For a given bioenergy land-use change, potential crop yield and the initial soil carbon stock are important variables in determining the impact on the net GHG balance, with high yields and low initial soil carbon offering the best opportunities for the lowest net GHG emission.

All conversions from forest show detrimental impacts on the resultant net field level GHG balance. This is as expected and is widely reflected in existing literature as well as our modelling work.

Modelling land-use change from arable to *Miscanthus*, SRC and SRF show beneficial changes in soil net GHG balance. For *Miscanthus* and SRC, this result is reflected in the literature whilst our field studies are neutral.

Land-use change from grassland to *Miscanthus* and Willow SRC was overall neutral in the literature and in our field studies. Our simulation modelling suggested a small detrimental and somewhat larger detrimental change on net GHG balance for land-use change from perennial grass to *Miscanthus* and Willow SRC, respectively.

In the modelling work, Willow SRC was found to be less beneficial than *Miscanthus* in terms of the soil net GHG balance. This was in part due to the lower predicted yield for Willow SRC compared to *Miscanthus*.

Nearly all of our field studies for SRF were ex-grassland locations, and these showed beneficial increases in soil carbon after transition. Further practical work is required to establish the impacts of land-use transitions to *Eucalyptus* sp. on soil net GHG balance. Our work was inconclusive due to the lack of available Eucalyptus field sites.

Where land-use change to a bioenergy crop shows a small detrimental impact on soil net GHG balance (e.g., from grass to *Miscanthus*, grass to SRF, forest to SRF), then management practices may be key to minimising this impact. Controlled field experiments are needed to establish best practices.

Further practical work extending to cover the whole cycle of bioenergy crop production would be beneficial, encapsulating climatic variation (including extremes), new varieties and planting regimes (which will directly affect plant yield estimates), and as of yet unexplored issues, such as land use reversion.

The extensive data generated within this project significantly extends the knowledge of bioenergy land-use change in the UK (and other temperate regions), and this will be available to other research teams. Together with making available the consistent methodologies developed and deployed within the ELUM project, this will allow other research teams to build upon and further extend the datasets, for instance, to consider a comprehensive life-cycle analysis approach to bioenergy land-use change. Furthermore, the ELUM modelling tool itself may be of interest to researchers, land-use planners and other agencies setting policy and managing the landscape and energy needs of the UK.