Programme Area: Bioenergy

Project: ELUM

Title: Identification of Existing Models, Toolkits and Resources for Assessing the Effects of Land Use Change

Abstract:

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

This deliverable presents a review of existing (2012) models, toolkits and resources available to assess the effects of a land use change to bioenergy crops from specified transitions. This report reviews the current (as of 2012) global literature covering the technological aspects of Work Package WP2 (chronosequencing approach to monitoring soil organic carbon), WP3 (dynamic approach to measuring soil carbon and atmospheric GHG emissions) and WP4 (numerical modelling approaches), specific to bioenergy land use transitions. The findings of this review were designed to further inform the design of the ETI's ELUM project experimental and modelling work from within the global scientific community. It was to provide key recommendations and help to guide the consortium as it delivered the ELUM project, and maintain cutting edge empirical and modelling work relevant to the development of sustainable bioenergy land-use transitions.

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Some information and/or data points will have been superseded by later peer review, please refer to updated papers published via www.elum.ac.uk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

Management & Deliverable Reference: PM04.1.1

A Review of Existing Models, Toolkits and Resources Available to Assess the Effects of Land Use Change Into Bioenergy Crops From Specified Transitions

REPORT

V 1.1

26-June-12

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EXECUTIVE SUMMARY

This report presents a critical review of existing models, toolkits and resources available to assess the effects of a land use change to bioenergy crops from specified transitions. This report underpins the on-going research in ELUM, since it reviews the current global literature covering the technological aspects of WP2, WP3 and WP4, specific to bioenergy land use transitions. The findings of this review will further inform the design of ELUM experimental and modelling work from within the global scientific community. It will provide key recommendations and help to guide the consortium as it seeks to extend the ELUM project and maintain cutting edge empirical and modelling work relevant to the development of sustainable bioenergy land-use transitions. The review looks beyond the toolkits currently used within ELUM and the wider community and reports on key cutting edge developments of relevance to ELUM.

This report utilises the systematic literature analysis of WP1 (D1.2) and identifies the toolkits, models and frameworks from the search terms of D1.2. This approach was taken to identify global trends in toolkit deployments within land use change to bioenergy research and avoid author biases to particular technologies or models. Toolkits and models are clearly defined and their role in quantification of soil carbon and soil and ecosystem greenhouse gas fluxes was defined. Models were classified as process-based or empirical and a whole soil vegetation coupled system, or an uncoupled system. A resulting 211 papers were reviewed at depth.

Following this analysis, the report identifies six key findings and eleven specific recommendations for the future development of ELUM to ensure the specific and more general questions related to bioenergy sustainability in a UK context are addressed. ***The key findings*** conclude that ELUM is broadly utilising appropriate technologies to address project objectives. In particular, ownership in the group of novel process-based models for Miscanthus and SRC is seen as a major advantage following several decades of model development and testing, from which ETI is taking benefit. It is also noted that the latest cutting-edge technologies for non-CO_2 GHG measurement are currently not available within ELUM across the network of measurement sites and this is a weakness. Similarly, the latest DNA- and RNA-based next generation sequencing technologies are not being deployed for microbial abundance and diversity, although expertise in the consortium in this area is good. Both of these limitations are the result of budget constraints. ***The specific recommendations*** include the development of a data-sharing platform for site data analysis and the widening of the project scope, to take benefit of the established network, to consider new research on ecosystem function and the delivery of ecosystem services.

CONTENTS

1.0. GLOSSARY OF TERMS

C	Carbon
CEH	Centre for Ecology & Hydrology
C_{eq}	Carbon Equivalents
CF-IRMS	Continuous flow, isotope ratio mass spectrometer
CHN	Carbon, Hydrogen, Nitrogen
CH_4	Methane
CO_2	Carbon Dioxide
CRDS	Cavity Ring-Down Spectroscopy
CRF	Carbon Response Function
DECC	Department for Energy and Climate Change
DEFRA	Department for Environment Food and Rural Affairs
DIAL	Differential Absorption LIDAR
DNA	Deoxyribonucleic Acid
DW	Dry Weight
EEA	European Environment Agency
E-FGA	Environmental – Functional Genomic Array
ELUM	Ecosystem Land Use Modelling
ESDB	European Soil Database
ETI	Energy Technologies Institute
EX-ACT	EX-Ante Carbon-balance Tool
FAO	Food and Agriculture Organization of the United Nations
FW	Fresh Weight
GC	Gas Chromatography
GC-ECD	Gas Chromatography – Electron Capture Detector
GC-FID	Gas Chromatography – Flame Ionization Detector
GC-IRGA	Gas Chromatography – Infrared Gas Analysis
GC-TCD	Gas Chromatography – Thermal Conductivity Detector
GHG	Green House Gas
GPS	Global Positioning System
H_2O	Water
HWSD	Harmonised World Soil Database
Hz	Hertz
IEA	International Energy Agency
INS	Inelastic Neutron Scattering
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IRGA	Infrared Gas Analyser
iTOC	Isotopic Carbon Analyzer
JULES	Joint UK Land Environment Simulator
LCA	Life Cycle Analysis
LCM	Land Cover Map
LIBS	Laser-Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging
LIFS	Laser induced fluorescence spectroscopy
LOI	Loss On Ignition
LUC	Land Use Change
MIR	Mid Infra-Red
MS	Mass Spectrometry
N	Nitrogen
NATMAP	National Soil Map

N_2O	Nitrous Oxide
NDIR	Non-dispersive infrared sensor
NDVI	Normalized Difference Vegetation Index
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Production
NGS	Next Generation Sequencing
NIR	Near Infra-Red
NMR	Nuclear Magnetic Resonance
NNFCC	National Non-Food Crops Centre
O	Oxygen
OA-ICOS	Off-Axis Integrated Cavity Output Spectroscopy
PAS	Photo Acoustic Spectroscopy
PLFA-GC-FID	Phospholipid-derived fatty acid – Gas Chromatography – Flame Ionisation Detection
PLFA-GS-MS	Phospholipid-derived fatty acid – Gas Chromatography- Mass Spectrometry
PRI	Photochemical Reflection Index
QCL	Quantum Cascade Laser
RMS	Root Mean Square
RNA	Ribonucleic Acid
rRNA	Ribosomal Ribonucleic Acid
S	Sulphur
SIP	Stable Isotope Probing
SIP-PLFA	Stable Isotope Probing - Phospholipid-derived fatty acid
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRC	Short Rotation Coppice
SVAT	Soil-Vegetation-Atmosphere-Transport
TCD	Thermal Conductivity Detector
TDLAS	Tuneable Diode Laser Absorption Spectroscopy
UK	United Kingdom
USDA	U.S. Department of Agriculture
VIS	Visible
VOC	Volatile Organic Carbons
WMS	Wavelength Modulation Spectroscopy
WP	Work Package
1G	First Generation
2G	Second Generation
16s rRNA	Component of 30S small-subunit ribosomal RNA

2.0. AIM

The aim of this report is to provide a review of currently available models, toolkits, resources and frameworks required to understand how a variety of land use change scenarios to bioenergy systems will impact on soil carbon balance and field scale GHG balance in a UK setting. This review will also assess the current cutting edge technologies not yet readily deployed in bioenergy studies and recommend toolkits, models and resources considered to develop and optimise current understandings.

3.0. INTRODUCTION

Bioenergy has the potential to benefit energy security and help to meet required reductions in greenhouse gas emissions (e.g. IPCC 2007, IEA 2010a). Currently European bioenergy production supplies 7% of total European primary energy (IEA, 2010) from 3% of cropland (3.1Mha), the feed stock for which is dominated by annual food crops - ‘conventional crops’ (Don et al., 2012) - or first generation bioenergy crops (1G). It is likely that future bioenergy feedstock will be provided, at least in part, by dedicated lignocellulosic crops - i.e., ‘second generation’ (2G) crops (Valentine et al., 2012). Within Europe, scenarios suggest that by 2030 some 44–53Mha of cultivated land could be used for bioenergy feedstock production (> 1000% increase of land use) (Fischer et al., 2010). The energy-oriented scenario includes an extra 19 MHa pasture land dedicated for second-generation biofuel production chains (Fisher et al., 2010). The European Biofuels Directive (Directive 2009/28/EC) states that biofuel crops must improve the whole life-cycle greenhouse gas (GHG) balance, by more than 35%, compared with fossil fuel life-cycles, rising to 50% in 2017 and 60% for biofuels from new plants in 2018 (Directive 2009/28/EC; Europa, 2010). One of the key emerging issues within calculations of such Life Cycle Analyses (LCA’s) are the lack of data underpinning the soil carbon (soil C) conservation and associated GHG balance of a land use change (LUC) to bioenergy. It is therefore imperative that robust procedures are established to spatially and temporally understand and predict the GHG balance and soil C stock implications of a land use change to a bioenergy cropping system, for both ‘conventional’ and ‘second generation’ crops. To achieve this, a ‘toolbox’ of techniques and approaches must be deployed to best effect, including experimentation and modelling and the development of novel technologies and their application to bioenergy systems.

This report will consider internationally available techniques and frameworks, ‘toolkits’ developed to quantify the impacts of a LUC to bioenergy crops on soil C and GHG emissions, and identify techniques appropriate to the temperate zone, using the UK as an exemplar. This will enable any gaps within ELUM to be addressed after year 1. This review is constrained to toolkits relating to an 'on field' assessment of soil organic carbon (SOC) and GHG balance. Thus, the toolkits underpin the development of more robust LCA approaches for the quantification of whole life cycle impacts of bioenergy, that utilise empirical, modelled and validated data, rather than look-up tables, as is often the case in many current LCA studies. LCAs *per se* as a toolkit were therefore not considered here. Similarly, in the process of this review up to 68 papers have been identified with the potential to inform on additional ecosystem service impacts of bioenergy cropping, but are beyond the scope of this current report and are dealt with later in the project (D1.4). Indeed the impacts of a LUC to bioenergy on soil C have been identified as the weak link in LCA analyses of net carbon equivalent (C_{eq}) impacts of bioenergy (Rowe, et al., 2009; Whittaker et al., 2010). Conceptually a LUC to bioenergy will encompass any biophysical and biogeochemical processes in the soil–vegetation–atmosphere continuum, and the resulting change in GHG and soil C. The site-specific factors influencing the GHG balance and SOC status are:

(i) Soil, subsoil and general environmental characteristics of the site
(ii) land-use history which will affect for example, current soil C stock, on-going changes in soil C and soil fertility and nutritional status
(iii) type of energy crop planted, and
(iv) management of the energy crop

These factors are all site-specific, requiring consistent approaches to enable robust comparative data to be collected, enabling extrapolation to wider scale importantly, if temporal GHG balance of the energy crop are to be made, then the net effect of this energy crop must be considered in relation to the effect of the preceding land use, retained over the same time period. Furthermore, some studies report SOC losses during the land-use transition to an energy crop (e.g., Don et al., 2011), therefore the GHG and SOC must also be considered throughout the transition phase and included in any annualised calculations (Kendall et al., 2009).

To understand the spatial and temporal implications of a LUC to bioenergy, the LUC system must be measured and modelled (to predict behaviour). It is within these two broad categories that the toolkits will be reviewed and they will be classed as either a) Measured: covers all toolkits concerned with quantification of measured and monitoring data derived from both the monitoring or manipulation categories or b) Modelling: any toolkit based on a computational simulation of SOC or GHG balance from a LUC to bioenergy designed to predict behaviour. Additionally, chronosequence as a methodology to assess LUC to bioenergy will be considered. The number of studies reporting an additional ecosystem service outcome (other than GHG and soil C) are also reported; however, the detailed analysis of other ecosystems service impacts will not be considered until deliverable D1.4, due in February 2013. Chronosequence methodology was reviewed in detail in WP2 deliverable (D2.1).

3.1. Toolkits for measuring GHG and soil C

Toolkits to assess soil C and GHG balance, the gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) will be considered across the whole soil-vegetation-atmosphere continuum. As recommended by the IPCC (2007), the net carbon equivalent (C_{eq}) flux to the atmosphere must be measured for bioenergy systems and these data underpin that overall calculation. The breakdown of C_{eq} from UK land use and agriculture is approximately 5% CO_2, 55% N_2O and 40% CH_4 in 2007 (DECC, 2008) and global emissions of CH_4 and N_2O have increased by 148% and 18% respectively, (IPCC 2007). In the UK, both CH_4 and N_2O are released disproportionately from livestock agriculture; for example, fertilised grazed grassland and manure handling release 60% of N_2O, and relatively little from arable cropland (15%) (Brown & Jarvis, 2001). However, in a purely arable context, changes in soil water content, pH and temperature will affect the balance between CH_4 production and oxidation and soil water content, nitrate content, pH, temperature and soil micro-organisms will affect N_2O emissions. A LUC to bioenergy cropping can affect these processes depending on site, land-use history and energy crop type (e.g., Grigal & Berguson, 1998). Carbon exchanges in the form of CO_2 are driven by the balance between vegetation photosynthesis and plant and soil respiration; additionally exchanges between the soil and the atmosphere can result from disturbances (e.g., Kurz & Apps, 1999, Myers-Smith et al., 2007), management (fertilisation, tillage etc.) (e.g., Boehmel et al., 2008, van Groenigen et al., 2011), the influence of the crop (rooting depth and structure e.g., Lohila et al., 2003) residue inputs (e.g., Blanco-Canqui & Lal, 2009) and the microbial community dynamics (e.g., King, 2011). Therefore, whether the land-use replaced by a bioenergy crop was, arable, pasture (with / without livestock), degraded, or natural, these three gases must be considered in the toolkits as must quantification of the soil C pool. In the UK, the upper 1 m of soil is estimated to contain around 4.6 Gt of carbon (Bradley et al., 2005), equivalent to nearly ten times the total CO_2 emissions of the UK in 2009 (DECC, 2011). Current agricultural practices deplete soil organic matter and contribute to soil erosion, this degradation has an estimated annual cost of £ 82 million and £ 45 million, respectively (DEFRA, 2009).

3.2. Toolkits for modelling

Models refer to a numerically based simulation of a LUC to a bioenergy crop and enabling predictions to be made of GHG balance for this transition. Models can be classed as either process-based or empirically derived. They should ideally incorporate a whole-system soil, vegetation, atmosphere transports approach (SVAT) of GHG's and water and include all, or components of, yield and soil C balance and benefit if they also include aspects of wider ecosystem services. These are fundamentally crop growth models and any modelling of whole fuel chains such as LCA is again outside of this report; however, LCA approaches used for SRC have been recently reviewed in Njakou Djomo et al., (2011).

3.3. Chronosequence

Chronosequence is a term given to a 'space for time' experimental approach from which current measures of soil properties (e.g. SOC) represent the influence of a multi-decadal time scale following a LUC to a bioenergy crop. This is achieved by identifying a series of energy crop plots in different aged plantations with presumed or documented similar management regimes, environmental conditions and land use history prior to conversion. The methodologies behind effective chronosequence approaches have been reviewed in detail in WP2 deliverable (D2.1). In the context of this review the experimental toolkits and models used in chronosequence studies will be reviewed and the outcomes from these toolkits will represent decadal scale values of a LUC. The findings will be discussed in relation to the findings from similar toolkits and models used in shorter time scale experiments.

4.0. METHODS

4.1. Review Criteria

Toolkits contributing to soil C and GHG measurements were grouped according to the following criteria which cover the nature of the sampling: spatial and temporal scale, the nature of quantification, the species quantified, user requirements and cost. Toolkits contributing to the modelling component were evaluated on the nature, scope and ability of the model and all review criteria are specified in point's i-iii below. For the 'current perspective', information on tool kits was taken from the current literature (all references provided as supplementary info). Future perspective includes upcoming technologies and cross-discipline technologies that could improve this tool kit collection; these will be derived from the most recent scientific literature and manufacturer's information. If applicable, papers using a secondary source of information will be discussed under resources.

(i) Toolkits for soil C quantification were evaluated according to:

(a) Source of report (peer, thesis, report, presentation).

(b) Species measured (SOC, C, SOM or other).

(c) Sampling (destructive, non-destructive, manual or automatic).

(d) Analysis technology (chemical, physical, biological or other, nature of the quantification process).

(e) Quantification type (direct, indirect).

(f) High tech resources needed (field and / or laboratory) (No for general lab equipment and consumables, yes for specialist equipment).

(g) Scale (i) spatial scale (low refers to a single area in the field, high the whole field and medium any measure in between, e.g. allowing for a random sampling approach). Within this component the physical depth of measurement will be referred to directly. (ii) Temporal scale (low is restricted to a single time point, high allows for decadal analysis and medium annual any measure in between.

(f) Resolution (i) spatial (low refers to a single measure at high scale, e.g. field, low a single defined point (≤ 1 m^2) and medium any measure between low and high). Depth resolution refers to the capacity to quantify by soil horizon and fraction, having this capacity will be considered high, horizon only medium and any other low.

(g) Redundancy (is there a need for supporting measurements, e.g. calibration, conversion).

(h) User input level (toolkit specific so not including sampling) (low: process is automatic; high refers to a manual process).

(i) Cost, unless specified in monetary terms, low refers to general lab / field equipment and consumables; medium, one piece of dedicated equipment, and high greater than one piece of dedicated equipment). This classification is a high level guide and it is acknowledged that a toolkit classed as medium cost could be more costly than that classed as high. Therefore wherever available the direct costs have been reported in the text.

(j) Special considerations (e.g., radioactivity needed, licensing needed, toxic chemicals used).

These toolkits are reviewed in section 5.1 and 5.3.

(k) Fits with ELUM – considers the current nature of the ELUM experimental infra-structure and methodologies. Yes, the toolkits could be deployed with no change to infra-structure or methodology. No, then an updated infra-structure or methodology would be required.

(ii) Toolkits for GHG quantification were evaluated according to the same criteria as for soil C except for (b) species measured refers to (CO_2, N_2O or CH_4) and (f) depth resolution now refers to a cross-section of the vertical ecosystem. A high depth resolution has the capacity to separate the fluxes between above and below ground and vegetation and soil; medium just above and below ground, and low has no such capacity.

These toolkits are reviewed in section 5.2 and 5.3

(iii) Toolkits for modelling were evaluated according to:

(a) Source of report (peer, thesis, report, presentation).

(b) Ecosystem process capacity (simulates vegetation growth, simulates soil processes or simulates both vegetation and soil processes in a coupled approach with feedbacks between one or all of the C, N and H_2O cycles)

(c) Energy crop species modelled.

(d) Simulation process (Empirical refers to a statistically derived approach using measured inputs and a Process-based approach refers to a mathematical simulation representing the relevant physiological, biophysical and physical processes).

(e) Dynamic inputs, refers to the amount and nature of inputs required to run the model additional to those for parameterisation. In the context of this report dynamic inputs will be evaluated on the capacity for the model to be up-scaled nationally or globally depending on available of mapped input data and how robust the model is to such data.

(f) Evaluation, has the modelled been evaluated using species specific measured data growing in the UK?

(g) Major outputs and minor outputs (are these of relevance to the assessment of a SOC and GHG balance resulting from a LUC to an energy crop for specified UK transitions and can they offer additional information?)

(h) Level of parameterisation, refers to the amount of input data required (other than the dynamic inputs) to drive the model to answer the users specific question (where small is 1-20 points, medium 21-50 and high >50 points),
(i) Spatial scale refers to the direct scale of the model (e.g. global, national, field or plant) it should be remembered the a plant or field scale model can have the capacity for up-scaling to national or global scale depending on the availability and response to the dynamic inputs (point (e) above).
(j) Temporal scale refers to the timeframe the simulation processes are run (High is ≤ minute, Low is ≥ annual and medium any time frame in between).
(h) Management refers to the capacity for the model to simulate agronomic, management practises, and where applicable these are reported.
These toolkits are reviewed in section 5.4

(iv) Chronosequence studies were evaluated according to:
a) Tools, models and techniques used
b) Data collected
c) Data modelled
These toolkits are reviewed in section 5.5

4.2. Literature analysis and toolkit breakdown

Considering the above, papers for the current perspectives were selected from a systematic review of the literature described in the following report to ETI (BI1001_PM04.1.3).

The 5855 unique papers resulting from the literature search of D1.2 were subjected to a broad high level scan in which they were designed as applicable, for instance, applying to a UK crop transition and in a temperate climate or not applicable – for instance, outside of these criteria. This broad high level scan of all 5855 papers also included a designation of research approach noting the following: (i) if a SOC or GHG value was quantified; (ii) if models were used; (iii) if a chronosequence was conducted; (iv) if a wider Ecosystem Service was considered. Those papers assigned an attribute (under i-iv above) numbered 514 for those papers designated as applicable and the attributes were distributed as shown in Figure 1.

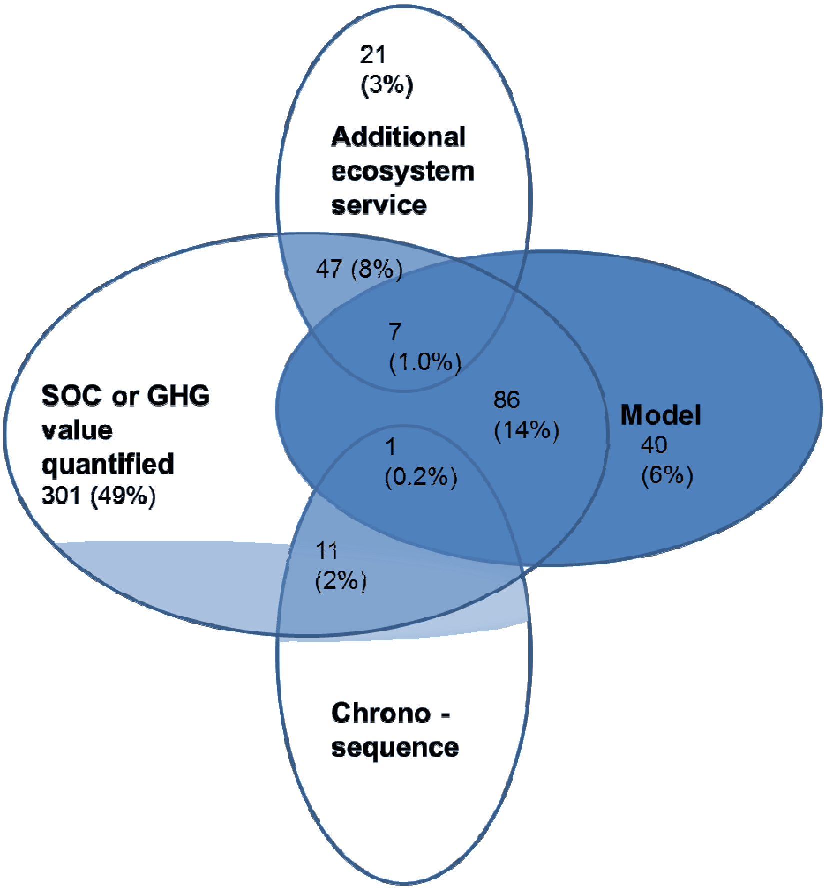

***Figure 1**: The distribution of toolkit types and inter-relations between toolkit types identified from the high level broad scan of the 516 papers assigned acceptable. Values represent number of papers and in parenthesis the percentage of the distribution.*

Those papers designated as not applicable numbered 5234. The 514 papers were taken for a deeper level review and assigned to a specific toolkit category, considering the above definitions of toolkit categories (sections 2.1-2.4) measurement or SOC and GHG value. After deeper review, 234 papers were excluded (e.g. LCA, meta-analysis, review or other literature). These papers were discounted as they were secondary to the toolkit defining the value. The remaining papers consisted of a toolkit giving primary measured or modelled data as described in toolkit criteria, or that used in a chronosequence approach numbered 211, and the distribution of these is given in Figure 2. A further 68 papers documenting an ecosystem service (additional to SOC and GHG balances) remain (Fig 1) for future analysis in D1.4.

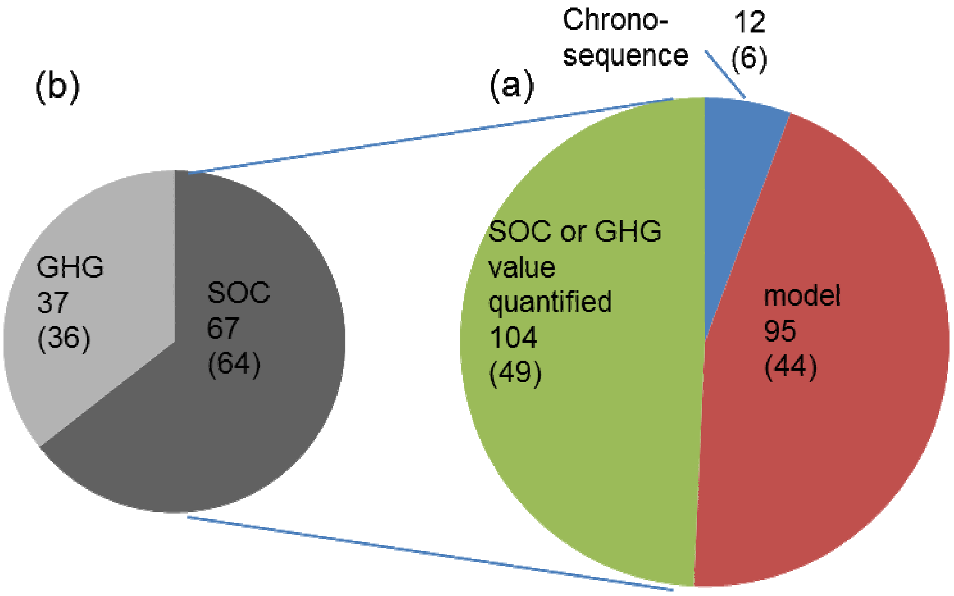

***Figure 2**: The distribution of toolkit types identified from the deeper reviewing of the 211 papers identified as contributing primary quantified values. Values represent number of papers and in parenthesis the percentage of the distribution.*

Summed together the modelling papers reported on a total of 36 different models spread across 1G and 2G energy crops.

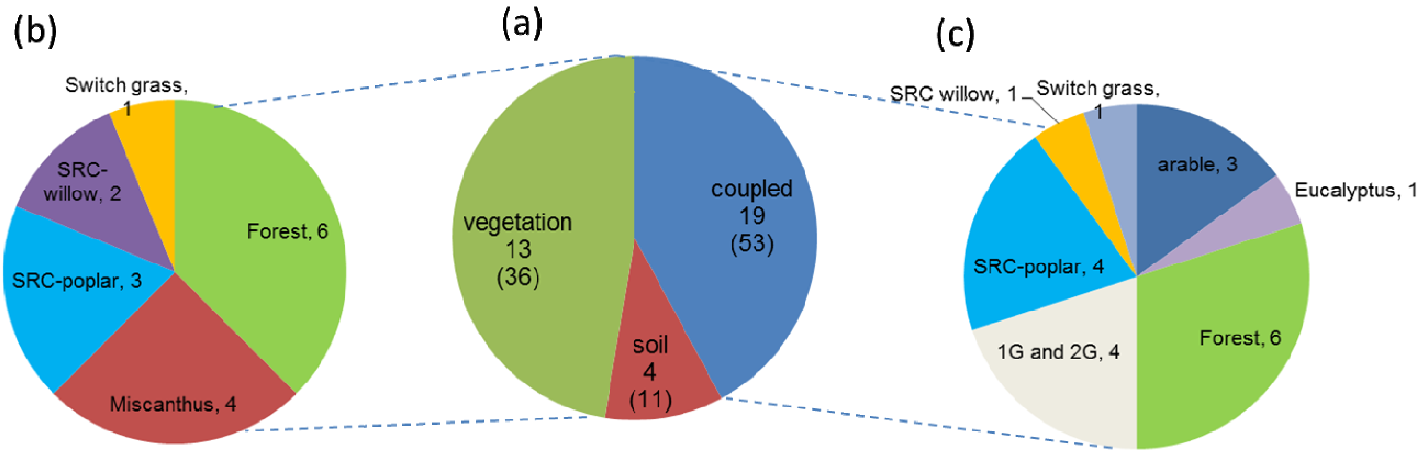

Figure 3*: An analysis of the 36 unique models identified from the literature search (a) the distribution of models to vegetation only, soil only or both vegetation and soil (coupled) (b) the number of unique vegetation only models assigned to energy crop type (c) the number of unique coupled models assigned to energy crop type.*

These models were grouped according to parameters given in the review criteria. This first order grouping defined the highest order component of LUC the model is simulating (i.e., is it vegetation processes, soil processes or a coupled soil-vegetation model?) and this is given in Figure 3a. The numbers of unique models representing an individual energy crop type for vegetation-only models are given in Figure 3b, and for coupled models in Figure 3c.

The papers focused on a chronosequence approach number 12. All papers have primary data on either SOC or GHG as measured by one of the reviewed toolkits and one paper has additional detailed with modelling work (Fig 1).

5.0. RESULTS

5.1. Soil carbon – perspectives from the current literature search

The papers reporting a toolkit used to quantify aspects of soil C from a primary measurement under a LUC to bioenergy were distributed as reported in Figure 3.

The nature of the toolkits as assessed by the review criteria are given in Table 1. Clearly absent from this list are any toolkits for large scale quantification, all kits require soil sampling and the scale is therefore constrained by the sampling regime. This is very unsatisfactory for user time required for sampling and for assessing heterogeneous landscapes. Furthermore, a number of the toolkits for SOC require a manual form of quantification, while on the positive side these are generally all low cost toolkits and the majority give a direct form of quantification.

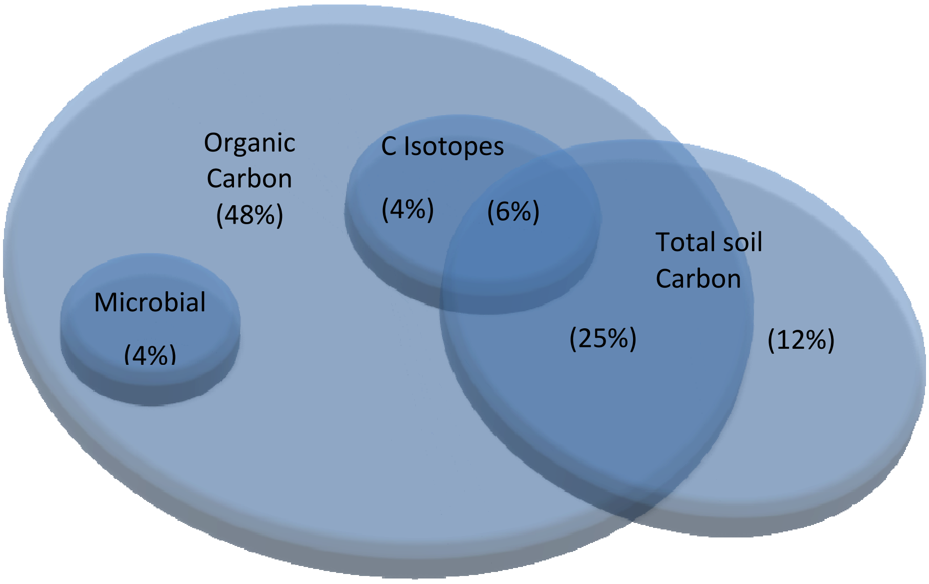

Figure 3: *The distribution of soil C components quantified within the papers reviewed.*

Toolkits used to assess SOC dominated this toolkit group (48%) with those assessing total soil C coming next (37%) and within these papers it was clear that multiple toolkits were used i.e., assessing both SOC and total soil C (25%).

5.1.1. A detailed review of the current perspectives on soil carbon toolkits extracted from the current literature search

The current toolkits for soil carbon quantification are all ex-situ and separate into manual wet chemical techniques for determining SOC and automated dry combustion techniques for determination of total soil C within the manually derived fraction(s) being quantified. Therefore, (a) the scale of the sampling e.g. large and heterogeneous, (b) the requirements from the soil C quantification (e.g. separated by horizons and fractions), (c) the nature of the soil carbon ((i) elemental e.g. graphite, charcoal (ii) inorganic e.g. carbonates (iii) organic, derived from the biotic land-use inputs) and (d) the available budget and labour will all need considering to determine the optimum toolkit.

Considering the requirement to quantify large scale land use, it is necessary for large spatial heterogeneity to be sampled, over an experimentally relatively short time period of transition that requires a high measurement resolution. Measurements must also be suitable as input data to

evaluate models (which requires fraction and horizon quantification).Finally, the toolkit must handle multiple samples rapidly with good repeatability and high measurement precision and resolution.
To assess the impacts of LUC to bioenergy on soil C, the idealised toolkit would offer a rapid, *in-situ*, non-destructive quantification of SOC to depth (max 1m) separated by horizon increments and with very high spatial resolution in a scanning mode to allow rapid spatial coverage with high precision, high measurement resolution across a wide measurement range.

From the existing literature (Table 1) and the above considerations, an automated dry combustion technique with pre-treatments to remove inorganic C and corrections for bulk density when expressed on an area basis would be optimal, over wet chemical, as confirmed below.

Table 1: *A summary of the toolkits extracted from the current literature and employed to quantify soil C. The list is therefore not representative of all possible available technologies – see table 3 for additional currently available technologies not identified from the current literature.*

Component measured	**Sampling**	**Pre-treatment**	**Quantification technology**	**Quantification type**	**High tech. lab.**	**High tech. field**	**Scale**	**User time**	**Cost**	**Considerations**	**Fits current ELUM**
SOC	Manual	Wet oxidation	Titration	Direct/ Manual	No	No	Small	High	Low	Harmful chemicals	Yes
	Manual	Wet oxidation	IRGA	Direct/ Manual	Yes	No	Small	High	Med	Harmful chemicals	Yes
	Manual	Wet oxidation	Calorimetric	Direct/ Manual	No	No	Small	High	Med	Harmful chemicals	Yes
	Manual	Wet oxidation	Gravimetric	Semi/ Manual	No	No	Small	High	Med	Harmful chemicals	Yes
	Manual	Dry combustion	NDIR	Direct/ Auto	Yes	No	Small	Low	Med	-	Yes
	Manual	Dry combustion	LOI	Semi/ Manual	No	No	Small	High	Low	-	Yes
	Manual	Automated	NDIR	Direct/ Auto	Yes	No	Small	Low	High	-	Yes
Microbial Biomass	Manual	Chloroform fumigation	Multiple	Semi/ Manual	Yes	No	Small	High	Med	Harmful chemicals	Yes
Total C	Manual	Dry combustion	NDIR	Direct/ Auto	Yes	No	Small	Low	Med	-	Yes
Total C and N	Manual	Dry Combustion	TCD	Direct/ Auto	Yes	No	Small	Low	Med	-	Yes
	Manual	Flash combustion	TCD	Direct/ Auto	Yes	No	Small	Low	High	-	Yes
13C:12C	Manual		NMR	Direct/ Auto	Yes	No	Small	Low	High	-	Yes
	Manual	Dry combustion	CF-IRMS	Direct/ Auto	Yes	No	Small	Low	High	-	Yes

Biomass Inputs – coarse roots	Manual	Dig, collect, sieve	FW and DW	Direct/ Manual	No	No	Small	High	Low	-	No
Fine roots	Manual	Rhizotron	Imaging	Semi/ Manual	No	Yes	Small	High	Med	Rhizotron setup	No
	Manual	Sequential coring	FW and DW	Direct/ Manual	No	No	Small	High	Low	-	No
Leaf litter	Manual	Trap	FW and DW	Direct/ Manual	No	No	Small	High	Low	-	Yes

5.1.1.1 Wet Chemical techniques

The standard wet chemical techniques all involve a chemical oxidation of the organic carbon and a manual form of quantification of either the amount of oxidant used (usually dichromate) defined as titrimetric and calorimetric in Table 1 or the CO_2 given off in the process defined as gravimetric or IRGA (Infrared Gas Analyser) in Table 1. This wet oxidation involves laboratory procedures of approximately 25 min per sample prior to quantification time. These techniques require general lab consumables and are therefore low cost. The 'gold standard' of these wet chemical approaches is the rapid dichromate Walkley-Black procedure (Walkley and Black, 1934) which has been the "reference" method for comparison of other toolkits and is a ***titrimetric*** process. In the Walkley and Black (1934) procedure SOM is oxidized to CO_2 with a solution containing potassium dichromate ($K_2Cr_2O_7$), sulphuric acid (H_2SO_4) and phosphoric acid (H_3PO_4).The amount of reduced $Cr_2O_7$is quantified through titration and assumed equal to the SOC content. However, due to incomplete oxidation giving recovery from 60 to 86% (Walkley and Black, 1934), a correction factor of 1.33 is often applied (mean recovery of 76%). However, the percentage recovery changes with soil type (Chaterjee, 2010) making this approach clearly unsuitable across heterogeneous soils unless recovery is calibrated (with a superior technique, e.g. dry combustion, but this is a duplication of work). Others have developed this technique by applying heat to overcome incomplete oxidation (e.g. Mebius, 1982) giving a recovery of 98% (when compared with dry combustion). This is a simple low cost standard procedure, however, it is laborious, involves hazardous chemicals with disposal requirements, carbon recovery varies with soil type, suffers from interference of other elements in recovery and quantification giving low precision (Schumacher et al., 1995). ***Calorimetric*** determination of this wet oxidation complex involves the use of spectroscopy to quantify either (i) the amount of unreacted dichromate or (ii) the amount of Cr^{3+} through a colour change reaction with s-diphenylcarbazide (Soon and Abboud, 1991) suggests this increases the precision of wet oxidation determination. Organic matter is determined ***gravimetrically*** as the difference between the initial and final sample weights following an H_2SO_4 hydrolysis of SOM. Correction for moisture content before and after hydrolysis is needed and as a conversion factor for SOM to SOC is needed this process is considered semi quantitative and the conversion factor will vary depending on the nature of the SOM, soil type and depth (Nelson and Sommers, 1996).

Wet chemical techniques have the advantage of being relatively simple, with minimal requirements, low cost and used globally. However the disadvantages are large: lengthy manual procedures, hazardous chemicals with disposal requirements, incomplete oxidation. They are often not a direct measure of SOC and need calibration and correction factors.

5.1.1.2. Dry combustion methods

The dry combustion methods involve physical oxidation of total soil C by controlled combustion, prior removal of inorganic C is required to quantify SOC.

The simplest of these toolkits is defined as ***Loss on ignition (LOI)*** and is a gravimetric analysis in which a dry sample is combusted in a crucible overnight (350 - 440℃) and the difference in mass after combustion is considered the SOM dry mass. A maximum temperature of 440℃ is used to avoid oxidation of the inorganic C. SOM needs correcting to SOC with errors as described for the wet chemical gravimetric technique (section 4.1.1.1.1) structural water loss from clays and hydroxyl groups may lead to over estimations, as may oxidation of inorganic C if not initially removed. This is simple, low cost and a global standard. However, it is an indirect measure requiring a SOM to SOC calibration and it is imprecise because the optimum temperature and combustion duration for complete SOM combustion vary with soil type. ***Automated dry combustion*** involves very high temperature combustion (>900℃) liberating all C as CO_2 and CO_2 is directly quantified by TCD, IRGA and indirectly following conversion to CH_4 by FID, typically referred to as CHN analysers. Prior to elemental quantification, the evolved gases are separated as C-oxides and N-oxides this can be achieved by GC or selective traps. High levels of C and / or N contents can result in an overlap on the GC column so reducing the accuracy of measurement; selective traps can be an advantage over GC for high C and N contents. Both TCD and IRGA quantification are global standards and offer similar resolutions, precision and range of quantification (0.02 – 400 mg C). TCD detectors measure the change in thermal conductivity of the sample gas and a reference. The IRGA quantifies CO_2 by detecting an energy level decrease in bands of the electromagnetic spectrum specifically absorbed by C=O bonds. The evolved CO_2 can be converted to CH_4 through a heated alumina coated with nickel in a hydrogen enriched atmosphere and quantified by FID. From the current literature the following companies dominate the CHN analyser market for soils:

(i) <u>LECO</u> maximum sample size 3 g <u>precision ± of 0.01%</u> (used in ELUM WP2),
(ii) <u>VARIO</u> from Elementar maximum sample load 5g uses selective traps and TCD C range from ppm to 100% (400 mg absolute) <u>precision ± 0.01%</u>
(iii) <u>PERKINELMER</u> sample size up to 0.5 g C measurement range 0.001 – 3.6 mg <u>precision ± 0.2%</u>

All instruments typically range in price from £40,000 to £50,000. These dry combustion techniques have the advantages of being fast, multiple automatic load capability (50 – 60 sample autosampler) and are the only approach allowing high throughput, precise measurement of SOC and they all have the capacity for N measurement (O and S can also be performed with some of the above). However, they are expensive and small sample sizes require the user to ensure samples are homogenised and representative, a process that can influence the status of the VOC content. The Vario MAX cube can load individual soil samples up to 5.0 g (the largest on the market) with a user defined combustion time and O_2 supply, therefore ensuring complete combustion of larger samples (previously a limitation to increasing sample size).

5.1.1.3. Toolkits for soil carbon - summary from the current bioenergy literature search

Soon and Abboud (1991) tested wet oxidation with titrametric, spectrophotometric and LOI quantification and dry combustion with IRGA quantification. Spectrophotometry was the most precise technique for quantifying SOC from wet oxidation, LOI was the least precise and considered unreliable for soil with low SOC and the automated dry combustion with IRGA detection was the most precise. Although the test of Soon and Abbound is over 20 years old it is still considered valid (Chatterjee et al., 2010).

5.1.1.4 Toolkits for measuring soil carbon – recommendation from the current bioenergy literature search

In summary, the current techniques suggest low cost, high precision and high-throughput cannot be achieved. The use of high temperature, automated, dry combustion techniques would be recommended from the current literature for measuring SOC (Table 1). This requires minimal sample preparation (drying), the high temperature ensures no carbon lost for quantification, a short and automated analysis time (5-10 minutes) and generally N content is also reported. However, sample fractionation is required to distinguish between carbon pools and inorganic C must be removed. ***Future developments are considered in section 7.0.***

5.1.2. A detailed review of the current perspectives on soil microbial carbon toolkits extracted from the current literature search.

To inform structural and functional changes to land undergoing a LUC to bioenergy, the idealised toolkit would offer information on microbial abundance, type and functions, in a rapid and sensitive methodology. Resulting from the current literature search only abundance is assessed and this is using chloroform fumigation. This is a low cost simple technique and a global standard. However, this is an ex-situ technique in which soils are fumigated with chloroform to lyse cells and release cellular C in proportion to the size of the biomass pools. Soil C is then quantified and the difference in C content with a non-fumigated sample used to determine the microbial biomass C. Absorption of chloroform to clay minerals leads to over estimation of C content in any clay containing soil and needs correcting for (Alessi et al., 2011)

5.1.2.1 A detailed review of available techniques for assessing soil microbes currently under-exploited in bioenergy LUC research.

Considering the short comings of chloroform fumigation and the availability of superior techniques, outlined in Table 2 the approach of chloroform fumigation would not be recommended.

High throughput DNA-and RNA-based technologies now exist to develop an understanding of soil microbial abundance, diversity and functional changes following a LUC to bioenergy. Examples of these technologies are (i) the small subunit (SSU or 16S) ribosomal RNA or its gene has been used extensively as a marker to classify microorganisms, this offers a survey of microbes present based on 16S ribosomal RNA (rRNA) sequences. However, no direct account of activity (ribosomal content may be a proxy for activity) or function is given and this approach is not considered to resolve at species level and is more likely taxon level (de Bruijn, 2011). (ii) Environmental functional gene array (E –FGA) (McGrath et al., 2010) for example Geochip (He et al., 2010) offers a high throughput array analysis of approximately 57, 000 gene variants from 292 functional gene families involved in carbon, nitrogen, phosphorus and sulphur cycles, energy metabolism, antibiotic resistance, metal resistance and organic contaminant degradation to help with understanding of below ground functioning. However, E-FGA require high quality nucleic acid from complex extractions for which protocol still need optimising, and data analysis is extremely complex with no universally agreed standards (He et al., 2012). In addition to this, the chips can only identify those probes present on the chip and thus important changes in diversity and abundance might be missed from non-coding DNA or from taxa not represented on the chip, so it is unlikely that these chips will have a long-term usage in the future.

Table 2: The currently available technologies for assessing the soil microbial biomass pool that were outside of the current literature search.

Species measured	**Sampling**	**Quantification type**	**Quantification Technology**
Microbial	Manual	Direct / auto	PLFA – GC-FID
Microbial	Manual	Direct / auto	PLFA – GC-MS
Microbial	Manual	Direct / auto	Nucleic acid hybridisation(NAH) – 16s R
Microbial	Manual	Direct / auto	NAH – E-FGA
Microbial	Manual	Direct / auto	NAH – Meta-genomics
Microbial	Manual	Direct / auto	NAH – Re-sequencing
Microbial 13:12 C	Manual	Direct / auto	SIP

(iii) Soil metagenomics (Daniel, 2005; Mackelprang, et al., 2011) which includes a variety of approaches that rely on isolation of soil DNA and RNA, either with or without the production and screening of clone libraries. This can provide a cultivation-independent assessment of the largely untapped genetic reservoir of soil microbial communities (diversity and abundance) and this approach has already led to the identification of novel biomolecules and begun to reveal the complexity of the soil microbiome in a variety of environments (iv) PLFA can offer total microbial biomass and community structure (Zelles et al., 1995) with a less demanding methodology and analysis than that required for nucleic acid approaches (vi) Stable Isotope Probing (SIP: Boschker et al., 1998; Radajewski et al., 2000) combines both stable isotope labelling for tracer studies (e.g. ^{13}C enrichment exposure) and tracing the label in microbial biomarkers. SIP can be used with PLFA allowing active component to be resolved at taxonomic level (Friedrich, 2006) or with nucleic acid hybridisation techniques to resolve species level activity and function (Chen and Murrell, 2010).

5.1.2.1 Soil microbial toolkits – recommendation from all available technologies

For functional attributes, microbial diversity and abundance, it is likely that in future, measurements will be focussed around DNA- and RNA-based next generation sequencing approaches. Although other techniques offer some advantage in identifying specific known groups, in general, the power of shot-gun NGS to identify unknowns far outweighs the advantages of other technologies. However, at present, PLFA approaches remain useful and cost-effective, particularly during times of ^{13}C feeding which would provide novel data and inform soil model development. SIP-PLFA resolves at the class level (Boschker et al. (1998) while SIP-nucleic acid is at the species level (Radajewski et al. 2000; Manefield et al.2002), however PLFA offers a greater detection of the incorporated label. It does not resolve function and structure as well as the nucleic acid approaches, but is a simpler and a less costly technology.

5.1.3. A detailed review of the current perspectives on soil C isotope toolkits extracted from the current literature search.

Quantifying soil C isotopes can provide information about the nature of the organic inputs and will be required following ^{13}C tracer studies providing novel and vital information on ecosystem processes and for model developments, calibration and evaluations. NMR and Mass spec have been identified as toolkits for isotope quantification from the current literature (Table 1).

5.1.3.1 Soil carbon isotopes – recommendation from available literature

For total soil C isotope the GC mass spec route would be recommended here as it can be directly coupled to an elemental analyser (section?) therefore reducing cost and sampling for isotope measurements. However, for microbial analyses SIP-PLFA would be recommended.

5.2. Greenhouse gases – perspectives from the current literature search

The papers reporting a toolkit used to quantify aspects of GHG from a primary measurement under a LUC to bioenergy were distributed as reported in Figure 4. Studies used to assess CO_2 dominated (65%) and studies assessing only CO_2 numbered 41%. Studies assessing N_2O-only, numbered 17%

while only 14% of studies assessed all three of the dominant GHG considered by the IPCC under a land use change context.

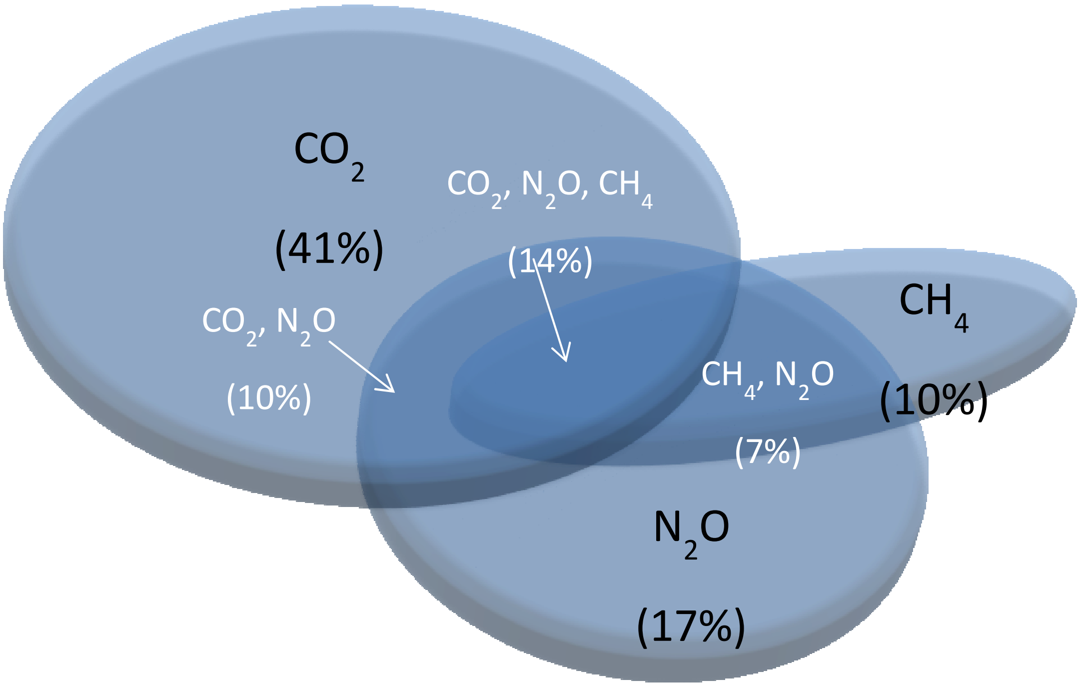

Figure 4: *The distribution of greenhouse gas species quantified within the papers reviewed.*

The natures of the toolkits as assessed by the review criteria and from the original literature search are given in Table 2. Within the GHG toolkits there is a move towards more automation than the soil C toolkits and particularly with eddy covariance technology automatic, direct field scale measurements are possible.

5.2.1 A detailed review of the current perspectives on toolkits for greenhouse gas quantification extracted from the current literature search

To measure the GHG fluxes resulting from a LUC to bioenergy; scale, precision and resolution need considering. Measurements need to represent the land area under change, therefore they need to operate at field scale, with a high resolution to account for spatial heterogeneity. They need to represent ecosystem processes on the vertical scale (i.e. measure emissions from soil, soil and roots, vegetation and whole system), this is only important for CO_2 due to the multiple ecosystem levels that influence CO_2 fluxes. Methane and N_2O fluxes result from the soil, although in 2006 Keppler et al., reported aerobic methane emissions from plants via pectin degradation. These emissions are now thought to be less significant than previously proposed (e.g. Nisbet et al., 2009, Dueck et al., 2007). Toolkits need to measure over long time periods (multiple years) with a high temporal resolution to capture rapid biological processes responding to abiotic and biotic events (e.g. diurnal variations, fertiliser applications, extreme sun or rain). From the current literature toolkits for GHG flux measurements can be separated into three groups (i) static closed chambers for soil fluxes (ii) dynamic automatic chambers for soil fluxes and (iii) eddy covariance technology for ecosystem fluxes.

5.2.1.1 Static closed chambers.

These are closed chambers for trapping gases over a user defined period of time, the gas samples are then taken and analysed ex situ. Chambers are cheap and easily deployed and should be replicated to account for site heterogeneity and large enough to minimise chamber edge effects, Chambers with larger areas exhibit less variability between replicates than smaller ones (Ambus et al., 1993) and minimal disturbance through chamber insertion. Chambers must allow for equilibrium with atmospheric pressure to avoid a chamber pressure gradient influencing soil GHG flux. For spatial extrapolation *in-situ* chambers measurements should be supported by site meteorology and soil moisture content and temperature to allow extrapolation of GHG flux and soil environmental condition relationships. The gaseous sample can then be quantified by either the high cost GC toolkits, IRGA (NDIR) or PAS. IRGA detects the absorption of infrared wavelengths emanating from a heated filament source that is characteristic of that gas. Absorption is measured relative to a gas free standard and GHG IR absorption bands can overlap typically with H_2O therefore H_2O removal is often required. PAS is similar to NDIR but IR absorption is measured directly therefore no need for a reference sample and has ppb detection limits with a 4 order of magnitude linear range.

5.2.1.2 Dynamic automatic survey chambers for CO_2 flux.

This toolkit is a mobile version of the static closed chamber in which the chamber is directly coupled to the gas analysis process in a hand held battery operated system. Chamber size is often smaller than for static chambers and in the current literature is limited to only CO_2 detection using IRGA. As for static closed chambers, this requires careful placement because inclusion of vegetation will cofound a measure of soil flux through photosynthesis and vegetation respiration, opaque chambers will reduce CO_2 flux from photosysnthesis. Nevertheless this mobile processes offers increased spatial and temporal deployment and real-time quantification. These toolkits are readily available from a number of highly regarded manufacturers for between £5000 – £10,000. Examples are, the ADC (0-3000 ppm @ 1ppm resolution) the PP system (0-2000 ppm optimal range @ 0.2 umol precision) and Qubit systems (0- 20000 pppm @ 1 resolution).

5.2.1.3 Eddy covariance technology for ecosystem fluxes.

The principle behind the eddy covariance technique requires the measurement of 3-D wind velocities and the gas concentration of interest at high frequency (e.g. 10 Hz). The vertical flux of gas is then measured as the covariance between the gas concentration and the vertical wind speed in the eddies over the crop. This is the most direct and defensible way to measure ecosystem gas fluxes (Burba and Anderson, 2011) but requires specific site characteristics, a number of peripheral environmental measurements (e.g. 3-D wind velocity at high speed, numerous meteorological data at high speed incoming and outgoing radiation and soil temperature and water content) for valid results along with complex data processing and interpretation.

Table 3: *A summary of the toolkits extracted from the current literature and employed to quantify greenhouse gases. The list is therefore not representative of all possible available technologies –*

Species measured	Sampling	Quantification Technology	Quantification type	High tech. lab	High tech. field	Scale	User time	Cost	Considerations	Fits current ELUM
CO_2 (soil)	Insitu/ Manual	GC-IRGA PAS	Direct/ Auto	Yes	No	Small	High	Med	Insitu chambers	Yes
	Dynamic/ Automatic	NDIR	Direct/ Auto	No	Yes	Med	Med	Med	Field power	Yes
CO_2 (EC)	Insitu/ automatic	EC - IRGA	Direct/ Auto	No	Yes	Large	Low	High	Field power	Yes
CH_4 (soil)	Insitu/ Manual	GC- FID	Direct/ Auto	No	Yes	Small	Low	High	Field power	No
N_2O (soil)	Insitu/ Manual	GC - ECD PAS	Direct/ Auto	No	Yes	Small	Low	High	Field power ECD – radioactive, licence required	No

Table 4: *A summary of existing toolkits available for GHG quantification that were not extracted from the current literature search but have the capacity to enhance experimental studies in LUC to bioenergy.*

Species measured	**Sampling**	**Quantification type**	**Quantification Technology**	**Company and web link**
CO_2, N_2O, CH_4	In situ and EC	Direct / auto	TDLAS (product now retired)	Campbell
CO_2, N_2O, CH_4	In situ and EC	Direct / auto	QCL	Aerodyne
CO_2, N_2O, CH_4	In situ and EC	Direct / auto	OA-ICOS	Los Gatos
CO_2, N_2O, CH_4	In situ and EC	Direct / auto	CDRS (under test for N_2O)	Picarro
CH_4	EC	Direct / auto	WMS	LICOR
CO_2, N_2O, CH_4	In situ	Direct / auto	QCL	Cascade technologies
	In situ	Direct / auto	NDIR	Lumasense Andros
	In situ	Direct / auto	PAS	Lumasence INNOVA
CO_2, N_2O, CH_4	Portable	Direct / auto	NDIR	ADC
CO_2	Portable – mapping capability	Direct / auto	IRGA + GIS capability	LICOR

From the current literature search, only CO_2 (and H_2O) was assessed by eddy covariance at cost (including the minimal peripheral measurements toolkits needed) of c £30,000. Globally 90% of toolkits for CO_2 flux by eddy covariance are provided by LiCOR as either 'open path' or enclosed path' the current NDIR CO_2 sensors from LiCOR provide (0 - 3000 ppm RMS of 0.16 ppm and capable of 20 Hz measurement frequency). Campbell are the next most abundant providing only 'open path' NDIR sensors (0-1000 ppm RMS of 0.15 ppm and capable of 50 Hz measurement frequency). Both are capable of off grid power due to low nominal power consumption (Campbell is reported 6 W and LiCOR 12 W). Data from these 'open path' systems can be invalid during rain, fog and snow events, this can be overcome using an 'enclosed' sensor however this requires more power and in general more maintenance.

5.2.1.4 Toolkits for measuring GHG fluxes - recommendation from the current bioenergy literature search

In summary and from the current literature search, where conditions allow, the use of eddy covariance technology for net ecosystem exchange (NEE) of CO_2 would be recommended. This should be supplemented with *in-situ* manual chambers quantified using a GC toolkit to inform spatial soil emissions of CH_4 and N_2O (i.e., representing the plot) supplemented with dynamic automatic chamber measurements of CO_2 to increase the temporal and spatial scale of measurement, and these dynamic measurements should be over bare soil with and without inclusion of roots.

5.3 Available toolkits currently under exploited in bioenergy research for GHG quantification.

Current existing or under testing toolkits for GHG flux measurements are available but did not appear in the current literature and these are reported in table 4. Deployment of such toolkits will offer advantages over these recommended from the current literature and these are discussed below.

5.3.1 High speed GHG technologies for eddy covariance method.

A number of companies have developed technology for high frequency measurements applicable for the eddy covariance technology based on direct laser absorption spectrometry (LAS) allowing eddy covariance measurement of a number of GHGs. The LAS technique is insensitive to small changes in absolute gas quantification due to high noise, and has been improved. Variants of LAS that are applicable to eddy covariance technique have been developed such as TDLAS (Campbell, but this is no longer in stock or production) for detection of CO_2, CH_4 and N_2O, CRDS (Picarro) for detection of CO_2 and CH_4, OA-ICOS (Los Gatos) CO_2, CH_4 and N_2O, WMS (LiCOR) for detection of CH_4 and QCL (Aerodyne) for CO_2, CH_4 and N_2O, the aerodyne QCL technology has also be used for eddy covariance measurements of C and O isotopes (Sturm et al., 2012), for which analysis scripts have been made available (Sturm et al., 2012). Others use PAS (INNOVA) CO_2, CH_4 and N_2O and PAS is similar to NDIR but IR absorption is measured directly therefore no need for a reference sample has ppb detection limits and a 4 order of magnitude range. See Table 4 for links to all companies and toolkits referred to here.

For quantification, the developments of LAS and PAS offer excellent sensitivity, precision and accuracy, real-time fast measurements (up to 20Hz) across a large dynamic range with high linearity. CRDS was a major advance delivering effective path lengths of 20 kilometers (or longer), resulting in parts per billion sensitivity using inexpensive near-infrared lasers. But CRDS is also extremely sensitive to physical disturbances (i.e., external factors such as temperature changes, pressure changes, and vibrations). These limitations are overcome in OA-ICOS (a fourth generation CRDS technology patented to los Gatos) which can be coupled with a VIS / NIR laser so increasing the species measurement capacity, they are also lower cost than CRDS, have improved reliability, lower maintenance needs increased sensitivity, precision and accuracy. For field applicability both CRDS and OA-ICOS are closed path systems which require considerable power, limiting their use to sites with mains power and they may also demand more maintenance than open path techniques. Additional to the open path CO_2 sensors only LiCOR offer open path, low power, detection of CH_4 using WMS. To increase the scope of GHGs measured by EC the technology exists, the user must now determine which is most appropriate for their requirements. For multiple and remote sites then the open path technologies from LiCOR have advantages of low power and low maintenance. Two companies offer a joint CO_2 and CH_4 eddy covariance package LiCOR at £47,328 and Los Gatos at ca. $40,000. Flux measurements of N_2O are more costly and currently limited to Los-Gatos at ca. $100,000, aerodyne and under test for PICARRO. The user would need to establish if eddy flux is needed for N_2O fluxes which are dominated by agronomic inputs such as fertilisers (i.e. does the transition have variable inputs) for which targeted chamber measurements around the time of input may be more cost effective and spatially resolved way to proceed.

5.3.1.1 Available toolkits for GHG measurement by eddy covariance - recommendations

LiCOR toolkits are fast becoming gold standard for eddy flux of CO_2 and CH_4 and the WMS approach of LiCOR has the advantages of working at ambient pressure in open path therefore no vacuum pumps and less power needs and WMS is less vulnerable to, and influenced by, mirror contamination with proven field scale detection (Dengel et al., 2011). LiCOR also offer integrated data formatting, logging and processing for both CO_2 and CH_4 flux in user friendly, free, gold standard software. LiCOR would be recommended ecosystem scale flux measurements of CO_2 and CH_4. If considered appropriate N_2O fluxes could be measured by eddy covariance technology at high cost and power demands currently from Los Gatos or Aerodyne, with the PICARRO system under final testing.

5.3.2 GHG technologies for soil chamber analysis.

The technologies reviewed in section 4.2.1.4.1 and developed by Aerodyne, Los Gatos, Picarro, INNOVA and Cascade technologies are all applicable to quantification of CO_2, CH_4 and N_2O using custom made or off-the-shelf in-situ automated chambers. However, these detection technologies are limited for in-situ automatic chamber quantification due to the high power needs generally met through mains power supply.

The ability to measure ecosystem flux of CH_4 at low cost and power (section 5.2.1.4) may meet all requirements as no compartmentalisation is required (section 5.2.1). Unlike CH_4, CO_2 fluxes do need compartmentalising; this increases the need for soil chamber studies (with and without root inclusion). The developed LAS technologies (reviewed in section 5.3.1) and the GC approaches (reviewed in section 5.2.1) have the advantage of allowing for C and O isotope discrimination, (and CH_4 and N_2O quantification) can be applied in-situ for these quantification toolkits with custom made or off- the-shelf automatic chambers, but at the need for mains power and high cost with limited spatial analysis. The most cost and power effective way for CO_2 quantification from in-situ soil chambers is direct IRGA technology for example LiCOR Li-8100A offers a four chamber multiplexed package (range 0 - 20,000 ppm 0.4 ppm precision and 1.5% accuracy) for £36,000. This toolkit has recently been adapted to a mobile geo-referenced system that is now available from LiCOR, (Li 8100a-S2) allowing soil CO_2 flux mapping at a cost of £15,000. N_2O fluxes are the result of soil specific aerobic (nitrification) and anaerobic (denitrification) processes, like methane they do not need compartmentalising therefore, if measured by eddy covariance there is less need for chamber studies (except to inform model developments with targeted spatial studies). In the absence of N_2O

measurements by eddy covariance then a mobile systems are a cheaper, more spatially informative and event specific deployable than in-situ automated chambers. Examples of mobile N_2O detectors are the INNOVA N_2O detection at 0.03 ppm CO_2 at 1.5 ppm, and the ADC portable gas analyser which offers mobile detection of N_2O and CO_2 (10 – 2000 ppm 10 ppm resolution) and CH_4 (at up to 1% with 100 ppm minimum detection) for ca. £3000. However, it is considered that the resolution of the ADC will not be sufficient for N_2O and CH_4 detection in low emission systems, such as many of the ELUM sites.

5.3.2.1 Available toolkits for GHG measurements from soil chambers - recommendation

All these under exploited technologies have advantages over those currently used in bioenergy research namely the capacity to measure CH_4 and N_2O at the ecosystem scale using eddy covariance technology (except for INNOVA technologies). If site characteristics allow for eddy covariance and with no cost or power limitations then eddy covariance measurement of all GHG should be carried out. Los Gatos, PICARRO and Aerodyne also allow eddy covariance of C and O isotopes and VOC compounds along with soil chamber approaches for CO_2 flux compartmentalisation.

5.3.3 Available toolkits for GHG flux measurements – a recommendation from a combination of eddy covariance and soil chamber toolkits

If power and cost are limited then LICOR open path technology should be used for CO_2 and CH_4 ecosystem fluxes (ca. £47,000). This can be supplemented with low cost and low power in-situ automatic chambers for high temporal resolution continuous CO_2 flux from both auto and hetero soil (ca. £36000). Supplemented with soil CO_2 flux mapping (£15000) at intervals (e.g. seasonal or freak events) to inform field scale heterogeneity and providing a rational to the siting of the in-situ soil chambers, that will still be needed for lower cost soil flux measurements of N_2O.

5.4. Models – perspectives from the current literature search

The thirty-six unique models identified from the literature meeting the review criteria are summarised in Table 5.

Taking account of the literature search methodology and the review criteria, 36% of papers reported a vegetation-only model specific to energy crops and 53% reported a soil-vegetation coupled model. The 11% reporting a soil-only model used the models RothC, YASSO, SUNDIAL and NOE2 (N_2O specific model) (Bessou et al., 2010). The next most informative level of the review criteria was to assign models based on the nature of the simulated output and the nature of the simulation process and these are reported in Tables 5 and 6.

The models reported in Tables 5 and 6 were identified from the literature search as already applied in a bioenergy context and within a temperate environment. This is therefore not an exhaustive list of potential models that can be developed or directly applied to bioenergy but rather, covers the most relevant resources and is a far wider scoping than recent reviews. The final choice of model or models depends on: (i) the specific question being asked and (ii) the availability of data to drive and then validate the model. For ELUM, the question being asked is about the stock changes of soil carbon and the GHG mitigation potential of bioenergy crops relative to other forms of land use. The model must also be developed to ensure that it is robust and driven by, spatially mapped driving data in an up-scaled mode, and have the capacity to generate outputs under scenarios of climate change. Several recent reviews have been conducted but only covering the fully coupled models in an attempt to identify the most suitable fulfilling these criteria. These include Chen et al., (2008) who identified DNDC and DAYCENT as the most robust for simulating N_2O emissions, and they identified *ecosys* and WNMM as having potential to become superior in terms of up-scaling, but cautioned that they required additional testing. Smith et al., (2012) suggests RothC, DNDC and CENTURY as suitable, however, RothC needs to be prescribed with organic inputs. These models except for WNMM and CENTURY have been captured from the literature search here, along with many more. CENTURY has been improved to DAYCENT by simulating a daily time step and DAYCENT is reviewed here. The Water and Nitrogen Management Model (WNMM) has not been captured in the literature search and for completeness is discussed here. WNMM was considered superior to DAYCENT and DNDC for simulating N_2O fluxes but this was only in one study (Li et al., 2005). Additionally ECOSSE (Smith et al., 2007) meets the criteria but has not been covered in these reviews and has not been identified in the literature search. This is possibly the result of an original limitation to organic soils, but ECOSSE is now also applicable to mineral soils (Smith et al., 2010). As for RothC (Coleman and Jenkinson, 1996; Zimmermann et al., 2007) ECOSSE does not simulate the crop growth and needs organic matter inputs, however, both RothC and ECOSSE have been developed and parameterised for UK soils. Furthermore, YASSO (Liski et al., 2005) was identified from the literature search, but has not been considered in the above reviews. YASSO is a soil model but only considers CO_2 flux and SOC (Tuomi et al., 2011).

In a UK context the idealised model (s) will simulate SOC stock, CO_2, N_2O and CH_4 fluxes and biomass yields in a physiologically meaningful way, at physiologically meaningful time and spatial resolutions. The model (s) should also have been evaluated on UK sites with measured data and have the capacity for spatial and temporal extrapolations. With this in mind the models have been separated by simulation process i.e., does the model mathematically represent biogeochemical processes (process-based), or are predictions developed from known biogeochemical statistical relationships (empirically-based)? In general empirical models should not be applied outside of the biogeochemical conditions for which the statistical relationships were developed. Therefore in order to model large heterogeneous landscapes and under future conditions of climate change, process-based models would be the model of choice. However, as empirical models are based on experimental evidence some suggest these are more appropriate than process-based models, when modelling is within the boundaries of the experimental evidence (Richter et al., 2008). In this context and in the absence of an appropriate process-based model if UK data exist then empirical models can be useful for deriving a ‘meta-model’ to allow wider spatial and temporal extrapolation, however, with larger uncertainties for predictions outside of the conditions of the original trials. To reduce these uncertainties measured yield curves defining the relationships must cover multiple management and climatic scenarios for a robust meta-model.

Table 4: *A summary of the unique vegetation-only models.*

Model Name (web link)	Energy crop Simulated	Simulation process	Major Outputs	Management simulation capacity	Reference specific to this model and bioenergy LUC
3PG	SRC-willow and poplar	Process	Above ground yield	Thinning and harvesting	Amichev et al. 2010; 2011
CBM-CFS3	Forest	Empirical	Above and below ground carbon stock	Not specified	Hagemann et al 2010
Richter et al., empirical model for miscanthus	Miscanthus	Empirical	Above ground yield	Not specified	Hillier et al. 2009
FORCARB	Forest	Empirical	Timber carbon	Not specified	Rauscher & Johnsen, 2004
GAMS - biofarm	Switch grass	Empirical	Biomass production	Not specified	Shastri et al.
LPJmL	SRC-poplar and Miscanthus	Process	Carbon and water fluxes	Harvest frequency	Beringer et al 2011
MISCANFOR	Miscanthus	Process	Above ground yield	Not specified	Hastings et al. 2009
MISCANMOD	Miscanthus	Process	Above ground yield	Not specified	Clifton-Brown et al. 2007
ORCHIDEE-FM	Forest	Process	Carbon, water and energy budget	Fertilisation, irrigation	Bellassen et al 2011
SIMA	Forest	Process	Above and below ground	Harvest frequency and fire	Routa 2011
STANDCARB	Forest	Empirical	Above ground yield	Not specified	Harmon et al 2009
Aylott et al., empirical model for SRC-poplar	Src-poplar	Empirical	Above ground yield	Not specified	Hillier et al. 2009
Woodstock with CWIZ	Forest	Empirical	Soil carbon	Thinning and harvest frequency	Meng et al2003

Table 5: *A summary of the unique soil vegetation coupled models*.

Model Name (web link)	Energy crop Simulated	Simulation Process	Major Outputs	Management simulation capacity	Reference specific to this model and bioenergy LUC
ALMANAC	Switchgrass	Process	Evapotranspiration, yields	Nutrients, weeds	McLaughlin et al.2006
CERES-EGC	Arable 1G	Process	GHG emissions	Tillage, fertilisation	Lehuger et al.2009
CO2FIX	Forest	Empirical	Tree carbon stock	Harvest rotations	Kaipainen et al.2004
CoupModel	Forest	Process	Soil carbon	Fertilisation and irrigation	Kleja et al2007
CQESTR	Multiple	Process	Soil carbon	Fertilisation, tillage practices, residue inputs	Liang et al2008
DAYCENT	Multiple	Process	Carbon and nitrogen fluxes	Fertilisation, tillage practices, residue inputs	Adler et al.2007
DNDC	Arable 1G	Process	GHG emissions, nitrate leaching	Fertilisation, , residue inputs	Tonitto et al2010
ecosys	Forest	Process	NEP, net ecosystem productivity	Fertilisation	Grant et al2010
ERGO	Forest	Empirical	Harvested biomass	Thinning, harvest frequency and type	Campbell et al., 1999
EPIC	Multiple	Process	Soil carbon	Yes	Izaurralde et al., 2006
FORSEE (4C)	SRC-poplar	Process	Above and below ground carbon stock	Thinning and harvest frequency	Lasch et al 2010
FullCAM	Eucalyptus	Process	Tree carbon stock	Yes	Cowie2008
GLOBIOM	Multiple	Empirical	Economic	Fertilisation and irrigation	Havlik e tal2011
Gorgan and Matthews - Forestry	SRC-willow	Process	Soil carbon	Harvest frequency	Grogan and Matthews 2002

GORCAM	SRC-poplar	Empirical	Carbon flux	Yes	Flynn and Ford2009
PnET	Forest	Process	Carbon flux	Not specified	Rauscher and Johnsen2004
RSPM 3.9	SRC-poplar	Process	Biomass carbon	Fertilisation	Garten et al.2011
SECRETS	SRC-poplar	Process	Above and below ground	Fertilisation, irrigation	Deckmyn et al. 2004
SWIM-SCN	Arable 1G	Process	Soil c and Hydrology	Not specified	Post et al2008

5.4.1 Review of the vegetation only models

5.4.1.1 Woody crops – Process-based models

The Physiological Principles in Predicting Growth the ***3Pg*** model (Landsberg and Waring 1997), has been specifically parameterised and evaluated for a *hybrid poplar* genotype (Amichev et al., 2010) and *willow* (Amichev et al., 2011) in Saskatchewan, Canada, although the model does not simulate a multi-stemmed system. *The model does not account for a multi-stemmed coppice and yield and carbon allocations (stem, leaf, root) are driven by allometric ratios, outputs are on a monthly time-step.*

The ***LPJml*** model (Sitch et al., 2003) the monthly input and output data are a gridded spatially explicit time series of global scale and coarse resolution. Grid cells may contain mosaics of one or several types of natural or agricultural (prescribed) vegetation which has been developed for SRC and miscanthus (Beringer et al., 2011). *This model is capable of a global coverage and evaluated at country scale for SRC, Miscanthus and switchgrass however, the scale is considered too coarse for a fieldscale UK study.*

The **SIMA-SRF** model was developed from SIMA (Kellomäki et al. 1992) and is a gap-type ecosystem model where model physiological processes determine diameter growth and gaps are determined by physiology and management and monte carlo simulation determine the stand evolution. SIMA-SRF has been parameterised for *parameterized for Scots pine, (P. sylvestris L.), Norway spruce [P. abies L. Karst], birch (Betula pendula Roth. and Betula pubescens Ehrh), aspen (Populus tremula L.) and grey alder (Alnus incana (L) Moench.)* in Finland (Routa, 2011) *The model explained between 75 and 85% of the measured variation in pine and spruce growth*, however, it works on an annual timestep, does not simulate root growth and would need evaluating for the UK.

The ORganizing Carbon and Hydrology In Dynamic Ecosystems ***ORCHIDEE*** model (Krinner et al 2005) is a regional to global scale model with 30 min resolved input met data, is linkable to outputs from a GCM, and contains a Forestry management module (FMM) (Bellassen et al., 2011). *This is too coarse scale for field studies and needs re-parameterising for SRF as current parameters are for 'broadleaf' and 'coniferous'.*

5.4.1.2 Woody crops – Empirical models

The Carbon Budget Model of the Canadian Forest Sector ***(CBM-CFS3)*** – is a forest model that implements a Tier 3 approach for forest LUC carbon accounting (Kurz et al., 2009) and is linked to the DSS for forest management 'Woodstock' (described later). Although built within the IPCC Tier 3 frameworks for GHG accounting from LUC, the above ground yields are prescribed from yield curves derived from measured data. These must first be established spatially and for the species of interest in the UK.

The ***FORCARB*** model developed by US forestry service (Rauscher & Johnsen, 2004) is an empirical model for forest timber carbon, timber volume and forest carbon pool evolution over time and with harvesting. This is based on US forestry inventories and would need UK SRF and has no accounting for GHG fluxes.

The ***STANDCARB 2.0*** (Harmon and Domingo, 2001) is a gap filling model where each cell represents a tree and simulates the accumulation of carbon over succession in multicellular mixed-species and mixed-aged forest stands and has been parameterised for Western hemlock and Douglas Fir (Harmon et al., 2009) with parameterisation it could represent SRF. However, the model works on an annual time step and has no accounting for additional GHGs.

The ***Woodstock*** model *(*Meng et al., 2003) is a forest management scheduling model offering a DSS for management optimisation strategies to a specified outcome. It requires input of current yield and yield curves and has no carbon or GHG accounting.

The ***UK SRC empirical*** model (Aylott et al., 2008) offers the largest dataset of UK SRC yields from 49 sites distributed across the UK and empirical yield models have been generated for the multiple genotypes of SRC willow and poplar at these sites. The UK evaluation with measured yields, explains between 50 and 75% of the measured variation depending on genotype and age. This is a valuable resource for predicting current above ground woody harvested yields which have been determined spatially for the UK (Aylott et al., 2010). However, the time step is coppice rotation (3 yearly) and lacks a definition of biomass allocation to roots and leaves needed for coupling to soil modules. Nevertheless, with assumptions about soil C inputs from these SRC yield maps, Hillier et al., (2009) calculated the SOC fluxes and stock by linkage to RothC to predict SOC changes on transition to SRC within England and Wales. The monoclonal growth trials sites (25) used for the empirical model were also used to evaluate the SRC process-based model ***ForestGrowth-SRC*** (Tallis et al., 2012) discussed in section.

5.4.1.3. Miscanthus - Process-based

The ***MISCANFOR*** model for Miscanthus yield (Hastings et al., 2009) is a development of **MISCANMOD** (Clifton-Brown et al., 2007) giving an improved descriptions of light interception, radiation use efficiency, temperature and water stress and has been evaluated with UK and EU measurements explaining 84% of the measured variations in yield using spatially mapped regional driving data. Peak yield is outputted and harvested dry matter is considered 0.66 of the peak yield (Clifton-Brown et al., 2007). MISCANFOR predicts above and below ground yields on a daily timestep and is therefore suited to coupling with the recommended soil models. The model works at field scale and has been up-scaled for the whole EU and although parameterised for *Miscanthus* X *giganteus,* MiscanFOR has the capacity to be parameterised for new genotypes.

5.4.1.4 Miscanthus- crops empirical

Richter et al., 2008 developed an empirical model specific for *Miscanthus* X *giganteus* from growth trial sites in the UK in which AWC explained *70% of measured yield variation in a UK evaluation*. This model has been extrapolated spatially across the whole UK and when driven by regional mapped soil and weather inputs the model uncertainty is increased by between 15 – 20 %. The model works on an annual time step and only predicts above ground yield.

The **GAMS**-approach used for switchgrass –GAMs is a mathematical framework employed here in a LCA bioenergy optimization DSS approach for Switch grass (Shastri, 2009). Original document from search not retrievable.

5.4.2 Review of the Soil vegetation directly coupled models

5.4.2.1 Woody crops Process-based

Grogan and Matthews (2002) developed a coupled model for SRC and forestry in which above ground yields are coupled to soil C turnover, the model is calibrated and evaluated for one site in the UK. Yields are calculated according to Beer's law so RUE and extinction co-efficient are the main parameters defining yield and yield allocation to different carbon pools are prescribed. Processes defining yield and the evaluation are limited; however***,*** this paper does offer parameters and definitions for linking carbon inputs with soil C turnover models.

The ***ForestGrowth-SRC model*** (Tallis et al., 2012) is outside of the literature search, only being recently accepted for publication (April 2012), but is within the ELUM consortium and used to deliver the BMVC project of ETI. ForestGrowth-SRC simulates carbon and water fluxes through vegetation and water fluxes through the soil vegetation system for multi-stemmed SRC poplar and SRC willow. Carbon fluxes summate yield on a daily time step separated by leaf, stem, coarse and fine root and *evaluated well with UK measured data explaining 91% and 85% of the measured variation in yield for SRC poplar and SRC Willow respectively.* The model is also developed for running in an up scaled mode for the UK (Tallis et al., 2012).

The ***RSPM 3.9*** model (Garten et al., 2011) works on an annual time step and simulates *SRC poplar* above and below ground biomass accumulation that drives soil carbon pool fluxes linked with an N fertilisation and harvesting modules. This model simulating soil C stocks under SRC poplar (Garten et al., 2011) has not been evaluated, but *the relatively simple approach can help inform a conceptual framework on which to link above ground yields with below ground C stocks*.

Stand to Ecosystem CaRbon and EvapoTranspiration Simulator ***SECRETS*** (Sampson et al., 2001) includes a soil C module (Thornley 1998) parameterised and evaluated for two *SRC poplar* clones at one site in Belgium (Deckmyn et al., 2004) and for *SRF Oak and Beech* forests (Deckmyn et al., 2004a). This module would need a UK evaluation to increase an understanding of the uncertainty and does not account for N_2O and CH_4 fluxes.

The ***CoupModel*** simulates the response to climate of aboveground biomass (based on RUE, of Monteith, 1977) litter formation and decomposition of organic matter and is built around a soil depth profile the SoilN model (Eckersten and Jansson, 1991) with easily available dynamic inputs (Svensson et al., 2008) so applicable for up-scaling. Although parameterised for Norwegian spruce it was not directly evaluated with yields and measured soil C, but could be parameterised and evaluated on UK SRF should data be available.

The **ECOSYS** model (Grant et al., 2010) works on field scale at a hourly timestep and is driven by microbial colonisation of organic debris (e.g. post-harvest) driving N mineralisation, root uptake and re-growth form which GPP was based on Farquhar et al., (1980). This is a highly parameterised model and has been *extensively evaluated at the hourly scale over for years using eddy covariance* CO_2 *flux data from three chronosequence conifer sites in different ecological zones of Canada*. This model could be valuable if parameterised and evaluated for UK SRF or SRC and *although* N_2O *and* CH_4 *fluxes are not implicit the descriptions of microbial processes could be developed for GHG flux predictions.*

The FOREST Ecosystems in a Changing Environment model ***FORSEE*** (***4C***) (Lasch et al 2005) has been parameterised and evaluated for both *SRC poplar* (Lasch et al., 2009) and many *SRF species* (Lasch et al., 2005) within Germany and has a soil hydrology and carbon module built with similar concepts and routines to SWIM-SCN (Post et al., 2007) (described later). It needs daily input climate data which may be an issue when considering future climates as spatial scenarios of future climates will need annualising. *This would need parameterising and evaluating in UK.*

5.4.2.2 Multiple crops process-based

The ***CQESTR*** model simulates the impacts of crop residue additions and crop and soil management to SOM stock changes, at the field scale on a daily time step over long-term simulations (100 yrs) (Liang et al., 2009). In North American trials the model predicts 95% of measured variation in SOM (Liang et al., 2009) and simulated the effects of residue removal and low tillage practises on SOM content very well (Gollany et al., 2010). *This model needs to be given yield inputs and does not include GHG fluxes but simulates SOM stocks very well under different environments, management and inputs.*

The ***Daycent*** model (Del Gross et al., 2005) is the daily timestep version of the CENTURY biogeochemical model (Parton et al., 1994). DAYCENT simulates yields (NPP) of a number of crop types and fluxes of C and N giving GHG emissions of *CO_2, and N_2O and also includes a CH_4* oxidation module. It does not contain microbial dynamics but offers an improvement on the Tier 1 emission factor approach when applied to North American agriculture, simulating *74% of the variation in measured N_2O emissions for cropping systems* (Del Grosso et al., 2005). DAYCENT has recently been applied globally (Del Grosso et al., 2009) to assess the impacts of tillage practices on global N_2O emissions. *No CH_4 evaluation has yet been reported and there is no representation of SOM below 20 cm.*

The DeNitrification-DeComposition model ***DNDC*** (Li, 2000) can be used for predicting crop growth, soil temperature and moisture regimes, soil carbon dynamics, nitrogen leaching, and emissions of trace gases *including nitrous oxide (N_2O), nitric oxide (NO), dinitrogen (N_2), ammonia (NH_3), methane (CH_4) and carbon dioxide (CO_2), on a daily time step and with different agronomic practices*. DNDC can run in a site or regional mode and is parameterised for a number of annual crops, grass and perennial grass. The ***PnET-N-DNDC*** model combines PnET model with DNDC to allow all *DNDC related outputs simulated for forest systems* (Giltrap et al., 2010). DNDC has been parameterised for a number of UK crops and UK specific conditions (UK-DNDC) and gave good *simulation of measured N_2O emission from 16 contrasting UK agriculture field sites on a daily time* *step* (Brown et al., 2002). *PnET-N-DNDC has been evaluated for forest N_2O emissions within the EU explaining 68% of the measured variation in N_2O fluxes across 19 forest sites* when initiated with regional soil and climate input data allowing EU wide mapping of forest N_2O emissions. (Kesik et al., 2005).

The ***FULLCAM*** model (Richards, 2001; Cowie et al., 2008) is essentially an integration of 3Pg and RothC for forests and CAMAg (Richards and Evans, 2000) with RothC for cropping systems so simulating carbon and nitrogen pools, plus interchanges and fluxes within the: plants, debris, mulch, soil, minerals, wood products, and atmosphere and can be run at field or regional scale (Richards, 2001; Cowie et al., 2008). FULLCAM has been applied to calculate the GHG balance of bioenergy and forestry in Australia including *parameterisation for Eucalyptus* (Cowie et al., 2008) and can therefore *offer a framework for model integration on a UK perspective.*

The ***PnET*** model (Aber and Federer, 1992) is a simple forest carbon and water balance model based on the interactions between leaf N, photosynthetic rate and stomatal conductance at a monthly time step (Aber and Federer, 1992) and improved to daily (PnET-Day) (Aber et al., 1996). PnET-CN (Aber et al., 1997) includes empirical functions for biomass turnover driving soil carbon and nitrogen cycle at monthly time step. PnET has been evaluated in North America forest sites, is simple to parameterize but operates at a monthly time step with simplified C and N turnover functions.

The ***CERES-EGC*** model (Gabrielle et al., 2006) is a crop yield model simulating the C, N and H_2O cycles and N_2O emission, where N_2O simulation uses the semi-empirical model *NOE* (Henault et al., 2005). SOM turnover in the plough layer is simulated by microbial sub modules NCSOIL (Molina et al., 1983). *CO_2 fluxes for maize and rapeseed were evaluated at the daily time step with data from eddy covariance and the model explained 81% of the measured variation but N_2O predictions were weaker (Lehuger et al., 2007).*

The ***EPIC*** model uses some concepts from CERES and is a field scale, daily time step model composed of physically based components for soil and crop processes such as *tillage, erosion, N and P cycling and crop growth and 80 crops are simulated by the same routine just differentiated by parameterisation* (Williams et al., 2006). EPIC has been evaluated for yield, C inputs to soil and SOC content, EPIC can also simulate multiple soil layers to depths of 3 m (Izaurralde et al., 2006). However, *the lack of explicit process representation of bioenergy crop types and no forest modelling reduce the capacity of EPIC in this context*. EPIC is the process representation of agriculture underlying a global a global recursively dynamic partial equilibrium model ***GLOBIOM*** which aims to give policy advice on land use competition between the major land-based production sectors

The ***ALMANAC*** model (Kiniry et al., 1992) is based on EPIC and is a daily time step growth model driven by light interception (Beer's law) RUE (Monteith) and soil water balance. ALMANAC has been parameterised for switch grass and simulates measured yields and WUE well (McLaughlin et al., 2006). ALMANAC is reported to simulate hybrid poplar yields but the only documentation can be found at the above link.

The ***SWIM-SCN*** model (Post et al., 2008) is based on SWIM, a crop, river basin model, which integrates hydrological processes, vegetation growth, water erosion, sediment fluxes and nutrient dynamics at the river basin scale (Krysanova et al., 1998, 2000). SWIM is coupled with soil C and N turnover modules SWIM-SCN and runs at regional scale (Post et al., 2008) *For long term average data soil C storage, yield and hydrology were all well simulated by SWIM-SCN within 148 000 km^2 of the ELBE river basin* (Post et al., 2008).

5.4.2.3 Fully coupled empirical models

The Graz / Oak Ridge Carbon Accounting Model ***(GORCAM)*** (Schlamadinger et al., 1997) is an accounting model that calculates the input/output balance of CO_2 fluxes from and to the atmosphere associated with bio-energy and forestry activities. *The C accounting is based on yield inputs derived from yield curves of known measured data.*

The ***CO2FIX*** model is a forestry carbon accounting model driven by known annual yield increments and then simulates carbon stocks within a forest system on an annual time step (Kaipainen et al., 2004).

The ***ERGO*** model (Campbell et al., 1999) is a GHG and energy budget model applicable to a wide range of bioenergy crops developed by Forest Research UK (Campbell et al., 1999) and *evaluated with a UK field study*. However, the *biomass yields are not modelled and the measured, estimated or projected yields are needed as an input.* The model is limited to C but updating for additional GHG fluxes is possible (Campbell et al., 1999).

5.4.3 Models - summary

An over-riding requirement to model the GHG balance and SOC stocks resulting from a LUC to bioenergy is that the model is evaluated with field data measured in the UK. With this in mind and from this review then the following vegetation only models could be considered. For woody crops including forestry and SRC (i) Aylott et al., 2008, (ii) ForestGrowth-SRC, (iii) Grogan and Matthews (2002) and (iv) the ERGO model. Miscanthusis represented by (i) MISCANFOR and (ii) Richter et al., (2008) and multiple crops by (i) UK-DNDC. Both Richter et al., 2008 Miscanthus yields and Aylott et al., 2008 SRC yields have been coupled to RothC to predict changes in SOC stocks resulting from a LUC to from existing arable, grassland and forest land use (Hillier et al., 2009). However, assumptions were made to derive a unit of C input from the modelled annual yields (Hillier et al., 2009) and work in Carbo-BioCrop and ELUM is addressing this limitation. The UK developed and evaluated soil GHG models ECOSSE and RothC should also be considered as appropriate. The global models DAYCENT and EPIC are also relevant, although the lack of species specific modules in EPIC and the lack of a UK evaluation rule them out.

5.4.4 Models - recommendation

The process-based models for Miscanthus - MISCANFOR (Hastings et al., 2009) and for SRC ForestGrowth-SRC (Tallis et al., 2012) are recommended as they offer equal or improved yield predictability over the empirical models, improved methodology for temporal and spatial extrapolation, a daily time step and yield partitioning to leaves, and woody above and below ground components for input to a soil GHG model removes the need for the assumptions of Hillier et al., (2009). However concepts and routines described in ECOSYS and RSPM 3.9 should be considered for optimisation and development of the coupling. For cropping systems UK-DNDC should be considered, as should the use of either RothC or ECOSSE as these have been UK evaluated. RothC or ECOSSE can be coupled with the wealth of spatially resolved crop specific UK yield data from DEFRA for current and near-future modelling e.g. 2020s (e.g. Hillier et al., 2009). A meta-model approach derived from these yield data coupled with RothC or ECOSSE could be used for future modelling (out to 2050s) considering a framework suggested by Ewert et al., (2005).

5.5 Chronosequence – perspectives from the current literature search

All twelve of the chronosequence papers have been reviewed to synthesize the transitions, techniques and toolkits that have currently been used (Table 7). In summary the current chronosequence studies are dominated by assessments of vegetation biomass (and biomass carbon) in nine papers, and soil carbon quantification, in nine papers with eight offering a quantification of both biomass and SOC. Only three papers offer an assessment of a GHG flux (CO_2) two measuring soil respiration (Arevalo et al., 2011; Jelinski et al., 2007) from static chambers with a mobile IRGA (Li-Cor). Arevalo et al. (2011) also use insitu automatic chambers (Vaisala CARBOCAP and Campbell data logger) for high temporal resolution. Both combine relationships of measured soil CO_2 flux and measured soil climatic conditions to derive a model of soil respiration on an annual scale at hourly resolution. The chronosequences studied by Grant et al., (2010), represent forest re-growth after clear felling. On three sites and over four year's net ecosystem production (NEP) was calculated from eddy covariance measurements of CO_2 fluxes and directly modelled with *ecosys*. Hourly CO_2 fluxes, annual NEP and above-ground biomass were calculated and modelled and model sensitivity to different harvesting practices following the clear-cut re-growth cycle were investigated.

5.5.1 Chronosequence summary and next steps

Overall conclusions from these studies are:

(i) Following transition multiple decades are needed to restore the SOC stocks to pre-transition levels, the duration is a function of the transition nature and type e.g. Foote et al., (2010). Arable to forest transition in which SOC accumulation was restricted to the upper 10 cm gave an increase of 32% after 100 years from the transition. In contrast, in a short-term (seven year) chronosequence with an arable to hybrid poplar transition, 7% of SOC was lost in the first two-years and pre-transition levels were re-gained after seven years (Avervalo et al., 2011).

(ii) The largest and most rapid changes in ecosystem carbon stocks were seen in the vegetation itself and this is again a function of the transition type (e.g. Avervalo et al., 2009).

(iii) On a decadal resolution following transition no measureable difference in SOC was determined at depths > 20 cm and this seems in dependent of the transition type.

The literature review (D1.2) will identify the transitions, age of transition and where documented the total SOC stocks by depth for the original land use and for the energy crop from temperate conditions for UK relevant transitions. The change in SOC with depth and time from these chronosequence studies will then be compared with the comparable changes calculated from modelled data and the much shorter-term experimental data. The outcome of these comparisons will be discussed in light of the findings.

5.5.2 Chronosequence toolkit recommendations

The nature of a chronosequence ‘as a space for time study’ reduces the need for highly temporally resolved measurements of SOC. It is recommended to have high spatial coverage of the site for soil coring, with an inclusion of the litter layer and organic layer for SOC determination by an automated dry combustion technique.

Over longer-term chronosequence sites NEP could be calculated with eddy covariance measurements of CO_2 exchange, and soil CO_2 fluxes from in-situ chambers. Appropriate models could then be parameterised and evaluated (e.g. Grant et al., 2010) and then run to simulate the transition history and again evaluated on current attributes e.g. SOC and biomass yields. Following a successful evaluation such a model would be considered highly robust for future projections.

Table 7: A summary of the chronosequence studies extracted from the literature search.

Crop type	**Transition from**	**Age of transition (years)**	**Toolkits**											**ref**
			Biomass (ag)	*Biomass (bg)*	*Site specific allometric*	*Leaf Litter*	*Other litter*	*Isotopes*	*Microbial*	*C (DC)*	*Max soil core depth (cm)*	*Soil fractions (mm)*	*GHG*	
Hybrid poplar	arable	2 and 9	DBH*	Fine root (coring)	No form literature	*In-situ* capture	line-intercept method***	Litter CF-IRMS	fumigation	DC****	50	0.25-2.0 0.05-0.25 0.002-0.05	-	1
Hybrid poplar	arable	2 and 9	DBH	Fine root (coring)	No form literature	From DBH	-	-	-	DC	50	-	CO_2 (soil)	2
Grasses	arable	60	-	-	-	-	-	-	-	DC	20	2 , 5	-	3
forest	arable	100	DBH	-	No form literature	-	-	-	-	DC	20	2, light	-	4
Forest	Forest	6 - 63	NEP from eddy covariance And direct measure										Eddy	5
forest	arable	8, 12, 19	DBH D10** Dcrown		yes	-	-	-	-	DC	-	-	-	6
Soya	Prairie	Tilled for 60yrs soya 1 yr	direct	Allometric from LAI	-	direct	-	-	-	DC	25	< 0.15	CO2 (soil)	7
Managed pine	Natural forest	8, 30, 35, 51	DBH	DBH	Yes inc. root	Direct	direct	-	-	DC	50	< 2.0	-	8
Eucalyptus	-	47, 85	DBH	DBH	Yes inc. root	-	-	-	-	-	-	-	-	9
Oak, spruce, pasture	arable	1-30 trees 21 pasture	-	-	-	-	-	-	-	DC	25	< 2.0	-	10
Hybrid poplar	arable	1-4 7-10	DBH	> 5 mm only	Yes inc. root					DC	50	< 2.0	-	11
Pine	Native Eucalyptus	2 - 24	-	-	-	-	-	-	-	Wet oxidation	50	-	-	12

(1, Avervalo et al., 2009; 2, Avervalo et al., 2011; 3, Breuer et al., 2006; 4, Foote et al., 2010; 5, Grant et al., 2010; 6, Jacobs et al., 2009; 7, Jelinski et al., 2007; 8, Li et al., 2011; 9, Razakamanarivo et al 2011; 10, Ritter et al., 2005; 11, Sartori et al., 2007; 12, Turner et al., 2000, *DBH, diameter at breast height (130 cm), **D10, diameter at 10 cm, *** line interception method of Halliwell and Apps, (1997) **** DC, dry combustion automated).

6.0. RESOURCES AND FRAMEWORKS

Resources and frameworks of relevance to ELUM, and available globally, are many and varied and recently reviewed in a global context by Smith et al., (2012), where the focus was on global-scale resources available to support the IPCC methodology framework for assessing LUC impacts on SOC. Here we distil available data to provide a comprehensive database of resources of relevance to ELUM in a UK context.

6.1 Available datasets, models, allied experiments and networks of relevance to ELUM in a UK context

6.1.1 Spatial datasets of relevance to ELUM

Spatial climate data

(i) past and current climate, Met office (5 Km2 and at least 50 years and for many parameters 98 years) (ii) future climate change containing probabilistic scenarios UKCP09 and spatially coherent for national up scaling UKCP09-SCP. At a 25 Km^2 resolution and for multiple emission scenarios.

Spatial soils data

(i) Harmonised World Soil Database (HWSD) (ii) European Soil Database (ESDB) from JRC and (iii) LandIS (NATMAP).

Both ESDB and HWSD give whole UK coverage unlike NATMAP (restricted to England and Wales).

Spatial land cover

(i) CORINE (ii) CEH landcover map 2007 (LCM 2007) or LCM 2000 and LCM 1990 as earlier versions. The UK LCM offer higher resolution than CORINE or GLOBCOVER and a broader range of UK specific land uses. The combination of LCM can offer nearly 2 decades of UK mapped landuse.

Spatial land management

(i) DEFRA NUTS1 level cereal yields

(ii) DEFRA energy crop yield maps and location descriptions (yield maps based on old models).

(iii) Natural England - Energy Crop Scheme (advice on planting and NUTS 1 statistics for Miscanthus and SRC to 2006).
(iv) The National-Non-food Crops Centre (NNFCC).
(v) The UK Countryside survey.
(vi) The Ecological Land Classification System (Forestry Commission)

Some of these and related model inputs have been reviewed in a report for the ETI within the ETI BVCM project (BI2002_WP01 01 by the BVCM consortium). To summarise, HWSD gives access to all of UK soils which is to date has not be available from NATMAP and HWSD allows for a global modelling framework to be developed. The UKCP09-SCP scenarios offer spatially coherent future climate data under three SRES scenarios A1FI, A1B1 and B1. The CEH LCM offers a finer spatial resolution than CORINE and is UK specific in terms of landcover types.

6.1.2. Experimental systems relevant to ELUM

Long-term experiments

In the UK Rothamsted, long-term experimental sites measuring soil characteristics from mid-19th century. These sites are used in a current project EXPEER to develop a network of sites to understand ecosystem change. The on-going soil projects through JRC should also be considered here e.g. DIGISOL, ECOFINDERS and ENVASSO.

EUROFLUX – aims to understand long term carbon dioxide and water vapour fluxes of European forests and interactions with the climate system. Has methodological information and analysis software including gap filling. LiCOR EDDY PRO - EddyPro™ is an open source software application developed, maintained and supported by LI-COR Biosciences. It originates from ECO2S, the Eddy COvariance COmmunity Software project, which was developed as part of the Infrastructure for Measurement of the European Carbon Cycle (IMECC-EU) research project.

6.2. Related Ecosystem carbon projects and resources

A list of ecosystem monitoring projects which can help inform ELUM activities.

1. ICOS – provides the long-term observations required to understand the present state and predict future behaviour of climate, the global carbon cycle and greenhouse gases emissions for Europe.

2. BIOCARBON TRACKER – offers global mapping of current stored biocarbon, biocarbon at risk and identifies opportunities for increasing biocarbon.
3. GLOBAL CARBON PROJECT – Aims to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them.
4. ILEAPS - aims to provide understanding of how interacting physical, chemical and biological processes transport and transform energy and matter through the land-atmosphere interface.
5. NEON – aims to enable understanding and forecasting of the impacts of climate change, land-use change and invasive species on continental-scale ecology -- by providing infrastructure and consistent methodologies to support research and education in these areas.
6. CARBOEUROPE - IP - aims to improve our understanding and capacity for predicting the European terrestrial carbon and greenhouse gas budget. This project has ended but is followed by GHG EUROPE.
7. CARBOEUROPE - a cluster of projects to understand and quantify the carbon balance of Europe.
8. GEOCARBON - Provide an aggregated set of harmonized global carbon data information (integrating the land, ocean, atmosphere and human dimension). Improve the assessment of global CH_4 sources and sinks and develop the CH_4 observing system component. Provide an economic assessment of the value of an enhanced Global Carbon Observing System
9. LTSEs – This global network of long-term soil-ecosystem experiments aims to improve quantification of soil change in response to land use change and decades long ecosystem development.
10. EXPEER - a consortium involving partner institutions in the EU, Israel, Norway, Serbia and Switzerland aims to develop existing national infrastructures, improve their research capacity and facilitate access to key experimental and observational platforms as well as analytical and modelling facilities.
11. EUROCHAR- A European network to assess the long-term stability and use of biochar in bioenergy systems for long-term C-sequestration.
12. EDGAR – Emission Database for Global Atmospheric Research. Stores global emission inventories of greenhouse gases and air pollutants from classified by anthropogenic sources and from 1970.

6.3. Related EU and UK networks in bioenergy

1. Algal Bioenergy Network - The purpose of the AB-SIG Network is to rapidly scope the environmental science potential in the area of algal bioenergy, and to build the research networks and secure the key partnerships needed to facilitate this. The Technology Strategy Board will partner this activity with NERC and, through their Biosciences Knowledge Transfer Network, will help to disseminate and transfer the knowledge gained through development of this Special Interest Group (AB-SIG).
2. Bioenergy NoE - EU Network of Excellence for Integrating activities to achieve new synergies in research to build a Virtual Bioenergy R&D Centre that will spearhead the development of a competitive bioenergy market in Europe.
3. Thermal Net - ThermalNet consists of three technologies: pyrolysis (Pyne), gasification (GasNet) and combustion (CombNet) and is funded through Altener in the Intelligent Energy for Europe Programme operated by DG TREN.
4. EPO-BIO - EPOBIO brings together world-class scientific and industrial expertise to identify areas for further investment in plant science research in order to realise the economic potential of plant-derived raw materials with long-term benefits to society
5. European Biomass Industry Association - EUBIA gathers organisations and companies from throughout the European Union. These companies range from long-known names in the world-wide energy sector to SMEs that are heavily involved in penetrating the energy market. Research centres are also well represented.
6. European Biomass Association - The European Biomass Association is a non -profit Brussels based international organisation founded in 1990 whose mission is to develop the market for sustainable bioenergy, and ensure favourable business conditions for its members.
7. EUBIONETIII - European bioenergy network III will analyse current and future biomass fuel market trends and biomass fuel prices. It will also collect feedback on the suitability of CEN 335 solid biofuel standard for trading of biofuels. Estimation on techno-economic potential of the biomass will be given until 2010 based on the existing studies and experts opinions.
8. European Biofuels Technology Platform - The Mission of the European Biofuels Technology Platform is to contribute to: (i) the development of cost-competitive world-class biofuels value chains (ii) to the creation of a healthy biofuels industry, and (iii) to accelerate the sustainable deployment of biofuels in the EU through a process of guidance, prioritisation and promotion of research, technology development and demonstration.

9. Renewable Energy Association - The Renewable Energy Association (REA) was established in 2001 to represent British renewable energy producers and promote the use of sustainable energy in the UK. The REA's main objective is to secure the best legislative and regulatory framework for expanding renewable energy production in the UK. The biomass trade association – British Biogen was incorporated into REA after its inception.

6.4. Agencies and governmental data sources

Below are the details of some key sources for information on energy crop statistics and policy developments, of relevance to UK and across Europe.

1. The International Energy Agency (IEA) (http://www.iea.org/)
2. The European Environment Agency (EEA) (http://www.eea.europa.eu/)
3. The Department for Environment Food and Rural Affairs (DEFRA) (http://archive.defra.gov.uk/foodfarm/growing/crops/industrial/energy/energy2.htm).
4. The Department for Energy and Climate Change (DECC) and the recently reported UK bioenergy strategy (http://www.decc.gov.uk/en/content/cms/meeting_energy/bioenergy/strategy/strategy.aspx)

6.5 International and National Frameworks

6.5.1 International - Global

Examples of frameworks designed to assist an assessment of bioenergy sustainability include globally (i) The Global Bioenergy Partnership 'Common Methodological Framework for GHG Lifecycle Analysis of Bioenergy' (ii) The United Nations Framework for sustainable Bioenergy (iii) The Bioenergy and Food Security Criteria and Indicators (BEFSCI) from the FAO. (iv) The IPCC (IPCC, 2006) has developed standard methods for estimating SOC changes and CO_2 and non CO_2 GHG emissions following a LUC. The methods are categorised as three Tiers, Tier 1 and 2 use default prescribed values (global for Tier 1, and national for Tier 2). At the Tier 3 level, site and case specific measured or process-based modelled data are used as inputs to calculate GHG emissions following a LUC. (v) The FAO has developed EX-ACT (Bockel et al., 2012) a spread sheet calculation tool developed from the IPCC 2006 standard methods for national GHG inventories. EX-ACT offers the user quantification of changes in land use and technologies foreseen by project components using specific "modules" (deforestation, afforestation and reforestation, annual/perennial crops, rice cultivation, grasslands, livestock, inputs, energy). Output is a computation of C-balance with and without the project using IPCC default values and when available specific co-efficients. Although used in many countries EX-ACT has not yet been used in the UK, a map of geographical usage is provided here. In a Brazilian case study (Branco et al., 2013) suggest that EX-ACT offers effective guidance to developers during project design identifying potential areas for development refinement. Recently (June 2012) the FAO have reviewed all GHG calculators in agriculture and forestry Colomb et al., (2012) and conclude that a wide scope of calculators exist (reviewed in Colomb et al., 2012) across management and land types, however, they suggest a need to improve accuracy of calculations by using more detailed input data.

6.5.2 International - European

At a European level and housed within the renewable energy targets for 2020 (Directive 2009/28/EC) are specific requirements for the biomass sector, divided between bioenergy and biofuel production systems. The Biomass Sustainability Report recommends (a) a general prohibition on the use of biomass from land converted from forest, other high carbon stock areas and highly biodiverse areas; (b) a common greenhouse gas calculation methodology which could be used to ensure that minimum greenhouse gas savings from biomass are at least 35% (rising to 50% in 2017 and 60% in 2018 for new installations) compared to the EU's fossil energy mix; (c) the differentiation of national support schemes in favour of installations that achieve high energy conversion efficiencies; and (d) monitoring of the origin of biomass. Within the Biofuels directive calculation methodologies are set out by which to calculate the whole life cycle biofuel chain GHG savings in comparison to a fossil fuel equivalent using the EU methodology, which is based on the IPCC Tier 1 approach, in which generic country wide emission factors are applied to the specified LUC.

6.5.3 National

The Department for Energy and Climate Change, 'UK Bioenergy Strategy' published by DECC April 2012 offers the most current and comprehensive framework for UK bioenergy. To summarise, this framework is based on 4 principles:

Principle 1: Policies that support bioenergy should deliver genuine carbon reductions that help meet UK carbon emissions objectives to 2050 and beyond. This assessment should look – to the best degree possible – at carbon impacts for the whole system, including indirect impacts such as ILUC, where appropriate, and any changes to carbon stores.

Principle 2: Support for bioenergy should make a cost effective contribution to UK carbon emission objectives in the context of overall energy goals. Bioenergy should be supported when it offers equivalent or lower carbon emissions for each unit of expenditure compared to alternative investments which also meet the requirements of the policies.

Principle 3: Support for bioenergy should aim to maximise the overall benefits and minimise costs (quantifiable and non-quantifiable) across the economy. Policy makers should consider the impacts and unintended consequences of policy interventions on the wider energy system and economy, including non-energy industries.

Principle 4: At regular intervals and when policies promote significant additional demand for bioenergy in the UK, beyond that envisaged by current use, policy makers should assess and respond to the impacts of this increased deployment. This assessment should include analysis of whether UK bioenergy demand is likely to significantly hinder the achievement of other objectives, such as maintaining food security, halting bio-diversity loss, achieving wider environmental outcomes or global development and poverty reduction.

ELUM addresses principle 1, and is providing direct, underpinning evidence: (1) information on carbon stock changes and GHG emissions (experimental) and (4) provides evidence for scenarios of increased demand (Modelling). This will also lead the way towards adopting an IPCC Tier 3 approach.

6.6 Summary

For mapped resources available for modelling it is recommended to use UK specific data except where the global datasets offers advantages e.g. currently HWSD. The experimental resources available should be queried for agreed protocols e.g. FLUXNET to allow ELUM to contribute globally and for analytical procedures e.g. EUROFLUX for approved gap-filling methods and LICOR for approved world-leading freely available flux analysis software EddyPRO. ELUM should establish techniques to complement the IPCC Tier 3 method of accounting for SOC changes and GHG emissions from a LUC to bioenergy.

7.0. FUTURE PERSPECTIVES – CUTTING EDGE TECHNOLOGIES

Section 4 considered all available toolkits models, resources and frameworks applicable to quantifying SOC and GHG emissions. This section will consider toolkits and frameworks under development and recently marketed in both soil C and GHG analyses. Additionally, toolkits considered enhancing both ELUM visibility in the global community and scientific impact will also be considered.

The review of the current literature identifies a clear absence of any toolkit for large spatial and temporal scale quantification that is automatic and therefore requires no sampling, i.e., it is non-destructive in nature. Such technologies do exist and examples are given below:

7.1 Toolkits for SOC quantification

7.1.1 Toolkits for in-situ real-time, non-destructive SOC quantification

1. Infrared Reflectance spectroscopy

This is a rapid approach offering a portable, *insitu* non-destructive technology with scanning capabilities. Near infra-red (NIR, 400–2500 nm) and mid infra-red (MIR, 2500–25000 nm) bands of the electromagnetic spectrum irradiate the soil and the reflected portions specific to interference by carbon bonds are quantified (e.g., McCarty et al., 2002). NIR reflectance spectroscopy rather than MIR as a method of soil C quantification is less influenced by soil moisture and is now available as a deeply-penetrating mobile scanning system (Christy, 2008), for example (http://www.veristech.com/products/visnir.aspx). However this needs to be towed behind a tractor and so is destructive in nature and would not fit with ELUM field sites, unless after harvesting of the annual crops; it needs calibrating to be truly quantitative, but it is fast becoming the approach for spatial mapping of soil C. High resolution satellite imagery may not be possible due to land cover interference with NIR and MIR bands, however Cécillon et al., (2009) suggest this approach can offer insights into soil C status and further aspects of health. The USDA infer SOC status nationally through the use of hyperspectral imagery (http://www.fia.fs.fed.us/Forest%20Carbon/default.asp).

2. Laser-Induced Breakdown Spectroscopy (LIBS)

This is a rapid approach offering a portable, field-deployable high spatial resolution (1 mm) soil C analysis. The LIBS method is based on atomic emission spectroscopy where a laser is focused on a solid sample forming a microplasm emitting and quantifying light characteristic of the elemental composition of the sample (Cremers et al., 2001). A portable system exists for environmental trace analysis (http://www.stellarnet-inc.com/public/download/PORTA-LIBS-Article.pdf) and in terms of soil C, portable systems are available at mm^2 resolution; however, soil texture, carbonate content and moisture influence the analysis leading to the need for multiple calibrations (Chatterjee et al., 2009). Nevertheless Da Silva et al. (2008) calibrated a portable LIBS system for quantitative measurements of carbon in whole soil samples from the Brazilian Savanna region.

3. Inelastic Neutron Scattering (INS)

Inelastic neutron scattering involves a neutron generator generating fast neutrons that penetrate the soil stimulating gamma rays and quantifying these rays, specific to elemental composition. The INS system was highly correlated and linear with known C contents in synthetic soils C (Carbon content 0 to 10%), r^2=0.99 (Wielopolski et al., 2008). Therefore considering the findings from the review of chronosequence studies (section 5) this may not be applicable to detect changes in the litter and organic soil horizons for example following arable to forest transition. However, in the field INS measurements were highly correlated with those from dry combustion across organic, pastureland and forest soils with up to 30 – 40% soil carbon content (R^2 = 0.99) (Wielopolski et al., 2011).This is a rapid, non-destructive portable; *in-situ* technology supporting multi-elemental analyses can measure large soil volumes (~ 0.3 m^3) in static mode or a scanning mode when towed with a tractor.

7.1.2 Toolkits for ex situ real-time, non-destructive SOC quantification

1. Laser induced fluorescence spectroscopy (LIFS)

This *ex situ* approach for characterising SOM and degree of humification developed by Milori et al. (2006) requires sample preparation. During LIFS the soil sample is excited by ultra-violet radiation and the back scatter fluorescence signals are used to quantify SOM.

7.1.3 Frameworks for SOC quantification

Toolkits that take a measurement can only quantify the 'here and now' models are needed to make future projections at decadal scale and inclusive of depth dependent processes. Part of the IPCC tier methodologies for carbon and GHG accounting includes the Tier 3 approach (IPCC pg 2.39). Within Tier 3 methods models are recommended to capture inter-annual variability and field-scale resolution of organic inputs and SOC changes. In a UK context such models have been reviewed in section and recommendations given. At a SOC stock change level, for such a modelling approach the IPCC recommend a set of bench mark sites to assess model predictions. Van Wesemael et al., 2011 have reviewed the global status of such a network and the requirements for the sampling. On a global scale both van Wesemael et al., (2011) and Smith et al., (2010) caution that this network does not yet cover all regions. On a UK scale there is a strong history of soil sampling and spatial maps which is on-going nationally through projects such as the countryside survey and a strong history of land use change monitoring and mapping for example the UK land cover map. Using a combination of past and present soil survey maps and land cover maps could be an approach to derive functions of SOC changes with LUC at a UK scale. This could be supported by measurements from specific LUC chronosequence, and monitoring sites. Similarly van Wesemael et al., (2010) took historic and current soil survey data for Belgium and using RothC identified the need for detailed and long-term accounting of land management practices e.g. use of residues, manure and tillage, to understand recent changes in SOC and highlight the need for monitoring networks to complement such studies. Furthermore, such a framework of using historic and current data could be used to test the carbon response functions (CRF) of Poeplau et al., (2011) if sufficient time resolution and LUC can be identified, and then derive future trajectories. Poeplau et al., (2011) reviewed 95 studies covering 322 sites and derived empirical relationships describing the SOC response (CRF) of crop, grassland and forest transitions to one another.

7.1.4 Toolkits for SOC summary

A toolkit for quantifying and mapping SOC the INS is recommended. This is because of the scanning, mobile capabilities, depth penetration and high correlation with dry combustion measurements.

Approaches for predicting future changes in SOC to depth and on a decadal timescale can be recommended as follows. (i) Through using process-based. (ii) Deriving empirical functions through a framework using historic and current mapped survey data supported with measurements from monitoring networks. (iii) Using the literature of measured data to derive SOC trajectory functions e.g. Poeplau et al., (2011) supported with measurements from monitoring networks.

7.2 Toolkits for GHG quantification

7.2.1 Developments in ecosystem GHG flux measurements.

The current literature suggests that much technology is already available for increasing the repertoires of eddy covariance measurements, provided by companies such as Los Gatos and Picarro (Table 3). These technologies also allow for quantification of CO_2, N_2O, CH_4 and volatile organic carbons (VOC) and isotopic discrimination at point source and field scale using eddy covariance technology. For further consideration, technologies based on LIDAR are emerging for the spatial mapping of GHG fluxes both in a horizontal and vertical profile and in real time (http://www.nist.gov/pml/div682/lidar.cfm). Differential Absorption LIDAR (DIAL), in contrast to other techniques, offers the opportunity to measure the concentrations of gases along a line-of-sight with a resolution of a few tens of metres, and with multiple measurements a three-dimensional distribution of gas can be mapped.

The ELUM network of flux sites would gain wider visibility and scientific impact by linking flux measurements with ecosystem optical spectra (for example NDVI and PRI). Specnet (http://specnet.info/) as a global community has only one UK site (Harwood forest). The aim of Specnet to develop satellite detection of ecosystem level fluxes would allow rapid inexpensive monitoring of the impacts of a LUC to bioenergy. Developing the ELUM flux network for this work would be relatively inexpensive (~£1500 for a canopy level optical sensor, e.g. http://www.skyeinstruments.com/).

7.2.2 Toolkits for GHG quantification summary

Considering these, future recommendation for GHG measurements still stand. However DIAL could complement with ecosystem flux mapping and depending on understory and a clear line of site could also be used for soil flux mapping. As an inexpensive addition spectral sensors could also be mounted at the network sites to complement existing global efforts to link ecosystem CO_2 fluxes with hyper-spectral signatures.

8.0 KEY FINDINGS

1. Currently soil C measurements are conducted by destructive manual sampling which is very time consuming. Automated dry combustion and an elemental analyser is the preferred toolkit for quantifying soil C. Novel non-destructive *in-situ* scanning technologies do exist and should be applied to this area of research, as apriority in future (section 7.1.4)
2. Eddy covariance is the recommended approach for ecosystem fluxes and new technologies allow for an increased repertoire of trace gas fluxes. These are currently not deployed in ELUM as they have a large capital outlay per site – £40,000 (CO_2 and CH_4) to in excess of £100,000 (N_2O) but should be considered for future research (section 7.2.2)
3. Toolkits for soil chamber studies can be optimised using a combination of *in-situ* automatic (for diurnal patterns) and manual (for spatial patterns) chamber sampling using cutting edge new technologies. Expertise in this area in ELUM is high and novel technologies are being deployed and tested, offering considerable value-added potential to the consortium and interaction with other projects (e.g. Carbo-BioCrop and EUROCHAR), (section 7.1.4)
4. Models covering all transitions included in the ELUM project are freely available, which is an advantage and the ELUM consortium has developed and holds a number of these models of global significance, particularly for Miscanthus and SRC, as well as novel models in development (sections 5.4.3, 5.4.4).
5. Novel DNA sequencing technologies are in a rapid phase of expansion and the ELUM consortium is well-placed to take advantage of these developments with two allied projects underway to test how soil micro-organism diversity and abundance are impacted by LUC to bioenergy. They are likely to outstrip any other currently available technologies and any investment in these current technologies should be viewed with caution (section 5.1.2.1)
6. ELUM will provide important information to national and international lregulatory authorities, helping to inform the development of sustainability criteria for bioenergy, in an area where empirical data are lacking. This original objective can be further enhanced in future by new research deploying latest technologies in GHG measurement and wider ecosystem services scope (section 6.5).

9.0 SPECIFIC RECOMMENDATIONS FOR THE ELUM PROJECT

Following this critical review of the experimental and modelling toolkits and related resources and frameworks to quantify soil C and GHG balance of a LUC to bioenergy within the UK the following recommendations can be made. Recommendations largely confirm ELUM is at the leading edge of readily available and utilised technologies (1-4). However, the critical review has identified key cutting edge toolkits that are available and deployable within ELUM to make ELUM a global leader (5-10).

1. Manual coring and quantification by automatic dry combustion techniques is the recommended current toolkit and approach for soil C quantification across heterogeneous landscapes. However, the in situ scanning and mapping capabilities of INS should be trialled (section 7.1.4)
2. Manual soil chamber sampling quantified by GC is the recommended current approach for obtaining large spatial data on soil GHG fluxes. However, the CO2 mapping system of LiCOR would offer considerable improvements (section 5.3.3).
3. Frameworks and resources exist for depth dependent and decade scale SOC measurements and these should be tested (section 7.1.4)
4. Eddy covariance is the recommended toolkit for obtaining ecosystem level GHG flux data. Measuring all GHG species with eddy covariance is recommended (section 5.3.2.1).
5. The use of a standard eddy flux data processing platform across the consortium should be implemented (section 6.6)
6. Crop-specific process-based models that are either coupled or have the capacity for coupling to soil C and GHG flux models are recommended. The use of UK evaluated species specific models is recommended (section 5.4.4) as is the use of historic mapped arable crop yield statistics (section 5.4.4).
7. Advances in optical spectroscopy toolkits can offer insights into quantification and mapping of soil C and vegetation CO_2 fluxes from satellite and ground level sensors (section 7.2.2).
8. Advances in LIDAR technology offers the capacity for 3-D GHG flux mapping at field scale, but these technologies are not yet fully developed and the consortium should keep a ‘watching brief’ in this area (7.2.2).
9. To develop the wider context of the ‘bioenergy sustainability’ question, the consortium should consider the link between ecosystem functioning and ecosystem service provision, ensuring alignment for national activities to assess ,’natural capital’,

developing new research in this area. Combining energy crop chronosequence studies with an ecosystem service provision to understand the long-term impacts on additional ecosystem services would plug a gap in the literature.

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