Programme Area: Bioenergy

Project: ELUM

Title: Report on the Effects of Land-Use Change (LUC) into Bioenergy Crops from Specified Transitions

Abstract:

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

This deliverable provides an up to date (2012) overview of relevant literature and has enabled the identification of consistent research messages and areas where uncertainties exist. In particular, there is a large dependency on models with limited sensitivity analysis or validation to predict the impact of Land Use Change on Greenhouse Gas (GHG) balance and changes in soil carbon stocks leading to carbon sequestration and net benefit to the system. Linking research at field scale, to activities in modelling in a multidisciplinary group such as that of ELUM, is world leading and of particular value to a wide range of stakeholders. This document outlines the full methodology for the literature search (as already provided for D1.3) and that for the meta-analysis.

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Some information and/or data points will have been superseded by later peer review, please refer to updated papers published via www.elum.ac.uk

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Report on the Effects of Land-Use Change (LUC) into Bioenergy Crops from Specified Transitions

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EXECUTIVE SUMMARY

We provide a detailed review of the effects of land-use change (LUC) to bioenergy cropping systems on greenhouse gas (GHG) emissions and soil processes in a UK context, alongside a consideration of management practices employed in bioenergy cultivation.

This deliverable is valuable to the ELUM project as it provides an up-to-date overview of relevant literature and has enabled us to identify consistent research messages and areas where uncertainties exist, which are summarised in the Conclusions of this Work Package 1 (WP1) report. Several current reports call for an increase in empirical data collection in this area, thus ELUM is timely. In particular, there is a large dependency on models with limited sensitivity analysis or validation to predict the impact of LUC on GHG balance and changes in soil carbon stocks leading to carbon sequestration and net benefit to the system. Linking research at field scale, to activities in modelling in a multidisciplinary group such as that of ELUM, is world leading and of particular value to a wide range of stakeholders.

This document outlines the full methodology for the literature search (as already provided for D1.3) and that for the meta-analysis. The pros and cons of the available software for the meta-analysis were investigated and MIX was chosen for its many analytical features and general usability. Following our review, the authors conclude with 10 summary points from the analysis, with recommendations outlined in the concluding section of the report.

Conclusions

- The site-based empirical data from both the network and chronosequence sampling are providing valuable empirical data for model testing, both within and external to the project. For example, the project is not considering whole life-cycle analysis (LCAs) and yet our data are of value in improving these tools for sustainability certification and assessment, particularly in a UK and European context.

- The site-based empirical data are of value, but the ELUM project will provide reliable data for between 2-3 years only which in most instances fails to follow even one full harvest cycle (SRF and SRC) and even for *Miscanthus*, gives limited insight into long-term changes in soil carbon fluxes and stocks.

- The review illustrates gaps in the literature. These are particularly apparent for forest transitions into first generation crops and uncertainties surrounding grassland transitions. For forests, the consortium should reconsider this transition, given the limited scope for enhanced planting of first generation crops for future feedstock supply and because in the UK context, de-forestation goes against current policy and is unlikely to be an important LUC.

- Analysis of the literature reveals limited soils data that assess the whole soil profile down to 1 m, and yet conflicting results on soil carbon sequestration are apparent when only top soil layers are considered.

- The consensus for transition from annual arable to perennial grass and SRC crops suggests improved Soil Organic Carbon (SOC), but the overall GHG balance to farm gate may be positive or negative and largely driven by fertilizer input and consequent N_2O emissions. Accumulation of SOC is in the range 0.44-1.1 Tonnes C ha^{-1} y^{-1}.

- There is likely to be a negative impact on GHG balance of transitions from grassland to first generation bioenergy cropping systems.

- The magnitude and direction of soil carbon change in relation to no-tillage treatments remains uncertain for bioenergy cropping systems but for second generation crops, with long rotation times, this may not be significant, although long-term experiments are warranted with soil profile sampling to 1 m.

- Quantitative data to compare the removal of residues for energy purposes or the remainder in the soil for sustainability and GHG balance are limited, but are likely to be crop specific. In the UK context, with future emphasis on SRC and *Miscanthus*, with minimum residues, this is likely to not be an issue of significant concern.

- Fertilizer application in bioenergy cropping systems may lead to large emissions of N_2O, contributing the most significant part of the GHG balance for these cropping systems. Future efforts to improve NUE (nitrogen use efficiency) are urgently required, as are management strategies to reduce unnecessary fertilizer use. There is a strong case for improved real-time instrumentation in the network of sites to capture this and other trace GHGs.

- There is adequate data to suggest cause for concern for crop water use in SRC and *Miscanthus*, since water use may be greater than other crop types and may outstrip ecosystem water supply. The impacts of water-use, and interaction with droughted environments for soil GHG balance remain to be elucidated.

Recommendations

- It is recommended that efforts are made to gain full impact of our research through better interaction with the LCA community and those developing sustainability toolkits for bioenergy in order to gain maximum impact from project results.

- It is recommended that the consortium maintain effort to extend and enhance the ELUM/CBC 'UK Bioenergy Network' including the addition of new work considering other ecosystem services, such as that in the recent NERC BESS application. This will gain maximum impacts from the sites for the benefit of UK policy makers and our scientific understanding of these crop transitions.

- It is recommended that more detailed consideration be given to the grassland to bioenergy transitions, since it is here where there is the largest paucity of data and because this represents an important transition for the UK. GHG benefits of this transition remain uncertain and may depend strong on management regime, fertilizer use and grazing, as well as the age and soil conditions. Given these caveats, generalisations are difficult. ELUM goes someway towards addressing this with three contrasting grassland transitions underway, but a side-by-side comparison of different grassland managements and bioenergy transitions would be valuable in future.

- It is recommended that ELUM continues with as much work as possible with soils to 1 m and that the grassland transition sites from both flux and chronosequence should be re-considered to ensure the maximum possible information will be available from them at the end of the project. A data matrix of these sites, with management and fertilizer inputs and C status of the soil should be constructed and considered for any additional action by the consortium.

Next steps will be focused on completion of the meta-analysis and provision of the final database, which is due by February 2013, with publication in the peer-reviewed literature where and when appropriate.

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1. AIMS

The aim of this deliverable is to provide a detailed review of the literature on the impacts of Land-Use Change (LUC) to bioenergy cropping systems in a UK-specific context, with emphasis on soil and greenhouse gas effects. The review provides a narrative of the systematic search undertaken as part of D1.3 (delivered April 2012) and underpins the delivery of the final meta-analysis database in D1.5 (to be delivered February 2013). This report describes the detailed methodology for the systematic review, the completed number of references currently in analysis and the detailed methodology adopted to undertake the meta-analysis, including choice of software and statistical approaches. The review is largely focused on the transitions from arable, grassland and forestry to bioenergy crops, including short rotation coppice (SRC) willow and poplar, *Miscanthus*, first generation crops and short rotation forestry (SRF). Where useful, other similar crops currently not grown for bioenergy in the UK are considered, for example switchgrass and maize, but crops from tropical zones were considered out of scope. Limited data are available for forestry transitions to UK-relevant bioenergy cropping systems and these are only briefly considered here. We review in detail, quantitatively and qualitatively, the effects of the transitions on soil organic carbon (SOC), greenhouse gas (GHG) emissions and on soil processes. The effect of different management practices – tillage, residue management, fertilizer and irrigation – have also been assessed for their effects on SOC and GHGs. The executive summary makes specific recommendations for and beyond ELUM, following our identification of research gaps and priorities.

2. METHODS

The literature search undertaken for this project was completed in a systematic manner to ensure that all relevant literature was captured. The search involved a structured search string and used three search engines which would allow us to capture peer reviewed scientific literature, government reports and other forms of grey literature. This search stage was comprised of 1024 unique searches which resulted in a total of 5786 individual references once duplicates were removed. These papers were firstly 'raw processed' by assignment of the categories 'useful' and 'not useful' based on a pre-defined selection criteria as outlined in the ETI contract. The criteria for section were:

- the location (to be UK applicable),

- the species concerned (inclusive of first and second generation bioenergy crops)

- the mention of the metrics which we used in the meta-analysis.

After this first round of processing, the papers were more carefully inspected to extract the data in pre-defined units for the meta-analysis, performing standard unit conversions if required.

The purpose of a meta-analysis is to review previously published data in a rigorous way to provide a quantitative result, based on a proper statistical analysis. It allows the data from many papers to be amalgamated to help us identify trends, patterns and identify variation between studies – this is particularly important in many areas in science due to large volumes of data that are published rapidly (Rosenthal & Dimatteo, 2001). The statistical package which will be used in this project is MIX due to its usability, regularity of updates and customer support.

See Appendix for full details of methodology.

3 LAND-USE CHANGE AND UK BIOENERGY CROPPING SYSTEMS

3.1 Introduction – the global and UK resource and policy perspective

It is now recognised that increased global demand for food, water and energy, alongside the predicted rise in global population and changes in climate, are placing natural resources under more pressure than ever before (Beddington, 2009; Godfray *et al.,* 2010) and at the centre of this larger demand for food and energy is the availability and sustainable use of a finite land resource that delivers multiple ecosystem services and goods (Valentine *et al.,* 2011). Competition for land is likely to intensify in future (Don *et al.,* 2012; Smith *et al.,* 2010; Smith *et al.,* 2012), although the role of bioenergy cropping systems in this intensification is relatively small, compared to the need to feed 9 billion people by the middle of the century. However, this need is likely to drive an increase in the area of land dedicated to agriculture, although as in the past, a large proportion of the gains in food production may be achieved through increased crop productivity per unit land area, rather than an increase in area of the landscape that is managed and farmed. Since 1970 global agricultural land area has increased by approximately 5%, whilst crop productivity has increased by more than 50%. Future increases in agricultural land vary from 5-30%, depending on the scenario considered (reported by Smith *et al.,* 2010), but all suggest increased land-use for agriculture and in contrast to the past fifty years, this food delivery must go hand-in-hand with other land-use pressures and in the face of climate change (IPCC, 2007). A consensus for future energy demand suggests an increase over the next few decades of between 30-50% on current-day supply (IEA, 2010), with renewable technologies, including bioenergy, playing an increasing role. Since feedstock supply also impacts on land-use, special consideration has been given in recent years to how this resource might be deployed in future. Certainly, Somerville *et al.,* (2011) estimated that less than 1 % of global agricultural land resource was in the past deployed to bioenergy but this is likely to increase in future and it is this increase, alongside that of food production and a requirement to fulfil the development goals of the Millennium Ecosystem Assessment (MEA, 2005), that provides the perfect storm described by Beddington (2009). In particular, and the focus here, is the impact of this LUC to bioenergy on the biogeochemistry of the soil and on soil processes and functioning (Hansen *et al.,* 1993; Grigel *et al.,* 1998; Grogan *et al.,* 2002; Gou and Gifford, 2002: Lemus and Lal, 2009; Hillier *et al.,* 2009).

The International Energy Agency (IEA, 2010) suggests that traditional biomass burning provides approximately one third of the energy in Africa, Asia and Latin America, with this figure being as high as 80-90% in the poorest countries around the world (Chow *et al.,* 2003; Demirbas, 2005). Currently, in a global context, bioenergy is the most significant renewable, contributing 78% of total renewables supply but remains largely under-utilised as an energy source (Somerville, 2007). The magnitude of the 'available, useable resource' as opposed to the 'technical potential' of global biomass availability has recently been questioned in several studies where quantification of the global resource has been attempted and these studies have been brought together by Slade *et al.,* (2011, Table 2). Some estimates suggest that there is potential to supply between 13-22% of the world's global energy demands by 2050 from biomass (Beringer *et al.,* 2011), whilst the IEA (2009), in one review, suggests 50% of global energy demand is technically possible from bioenergy, whilst other studies suggest biomass potentially available to supply the entire energy demand of 2050.

Study Label	Full reference
Bauen04	Bauen, A., Woods, J. and Hailes, R. (2004) Bioelectricity Vision: achieving 15% of electricity from biomass in OECD countries by 2020. E4tech (UK) Ltd.
Beringer11	Beringer, T., Lucht, W. and Schaphoff, S. (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy, 3, 299-312
Cannell02	Cannell, M. G. R. (2003) Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. Biomass and Bioenergy, 24 97-116
deVries07	de Vries, B. J. M., van Vuuren, D. P. and Hoogwijk, M. M. (2007) Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. Energy Policy, 35 2590-2610.
Erb09	Erb, K.-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, J. K., Müller, C., Bondeau, A., Waha, K. and Pollack, G. (2009) Eating the planet: Feeding and fuelling the world sustainably, fairly and humanely - a scoping study (Commissioned by Compassion in World Farming and Friends of the Earth UK). Institute of Social Ecology and PIK Potsdam, Vienna, Potsdam.
Field08	Field, C. B., Campbell, J. E. and Lobell, D. B. (2008) Biomass energy: the scale of the potential resource. Trends in Ecology and Evolution, 23.

Fischer01	Fischer, G. and Schrattenholzer, L. (2001) Global bioenergy potentials through 2050. Biomass and Bioenergy, 20, 151-159.
Haberl10	Haberl, H., Beringer, T., Bhattacharya, S. C., Erb, K.H. and Hoogwijk, M. (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints Current Opinion in Environmental Sustainability, 2.
Hall93	Hall, D. O., Rosillo-Calle, F., Williams, R. H. and Woods, J. (1993) Biomass for Energy: Supply Prospects. IN T.B. JOHANSSON ET AL (Ed.) Renewable Energy: Sources for Fuels and Electricity. Washington, D.C, Island Press.
Hoogwijk03	Hoogwijk, M., Faaij, A., van den Broeka, R., Berndes, G., Gielen, D. and Turkenburg, W. (2003) Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy, 25, 119 - 133.
Hoogwijk04	Hoogwijk, M. M. (2004) On the global and regional potential of renewable energy sources. RIVM, University of Utrecht.
Hoogwijk05	Hoogwijk, M., Faaij, A. and Eickhout, B. (2005) Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass and Bioenergy, 29 225-257.
IEA08	IEA (2008) World energy outlook. International Energy Agency (IEA).
IEA 2010	IEA (2010) Energy technology perspectives 2010: scenarios and strategies to 2050. International Energy Agency (IEA), Paris.

Table 2 - A summary of several recent reports that attempt to estimate the global biomass resource suitable for bioenergy utilisation. For a full list of these reports please see Slade et al. (2011).

Slade *et al.* (2011) have reviewed these studies and given a detailed account of the assumptions underlying these highly contrasting estimates of global biomass potential for bioenergy. Briefly, they include yield assumptions, technology enhancements for yield (including breeding and GM), inputs such as nitrogen fertilizer and water, with many relying on yield models that include an array of underlying assumptions, land conversions that include soil rich in biodiversity and carbon and grazing land that may or may not become available. However, in the context of the review presented here, the global perspective is of limited significance except to say that the biomass resource is considerable and even with moderate future predications, between 10-20% of future energy demand could potentially be supplied from biomass resources (Slade *et al.,* 2011), with 10% considered more appropriate for UK supply by the recent Committee on Climate Change review (CCC, 2011). In the CCC review, four scenarios for land-use were considered, to estimate global biomass availability with bioenergy crop deployment ranging from 100 Mha to 700 Mha of bioenergy cropping. Given the global land area was estimated at 13,000 Mha and agricultural land at 4,200 Mha. Of this approximately 1,550 Mha is currently used for crop growth and it is suggested globally, that 500 Mha may be available from abandoned agricultural land. Most significant here is the UK resource, where much more detailed spatial and temporal analysis is completed or is underway within the Biomass Systems Value Chain Modelling (BVCM, ETI) project where the system boundary of the UK land-mass is used, with imports considered separately.

In the UK context, the 'Energy Crop Scheme' provided by Natural England is a Government incentive program to encourage farmers to plant second generation, dedicated lignocellulosic energy crops in the UK, in the belief that these crops represent a better GHG balance than arable crops and because they may be grown on land not suitable for high yielding arable cropping (DECC, 2012; CCC, 2011; report, Royal Society, 2008). A grant of up to 50% for the cost of the plantation is awarded for approved energy crops which include SRC trees and *Miscanthus* (Natural England, 2009), but despite this, uptake of these grants has been poor, targeted as they are to the planting rather than the harvest and profit of the crop. Poor uptake reflects a complexity of concerns expressed by growers and these extend beyond financial considerations. Sherrington *et al.* (2008; 2010) identified concerns over long-term contracts, long-term commitment of land to difficult crops and rooting systems and lower returns compared to annual crops, all contributing to poor uptake. However, they also noted that *Miscanthus* appeared to show higher gross margins than willow. A more effective Government approach could be initiated to provide guarantees for long-term security of income to enable the industry to flourish. Enabling the price of carbon and carbon credits to be used as a metric in such circumstances may provide the way forward, but for such, a clear empirical evidence base of GHG benefits and costs of different land use would be required for the UK and this remains limited for SRC and *Miscanthus*, and is only now being addressed at the research level. Within Europe, the UK is under-represented for natural biomass resources, ranking 19 out of 27 countries for forest resources (Global Forest Resources Assessment, 2005), although it has been highlighted that this still represents a significant and large source of biomass for the UK. That biomass resource could be available through better management of private forests, providing up to 2 million tonnes of wood annually, for energy uses (Forestry Commission, 2009). Current estimates of the UK land area use for energy crops are 7365 ha for *Miscanthus* and 2131 ha for SRC willow

(Digest of UK Energy Statistics, 2012). The use of short-rotation coppice cultures have a double benefit in terms of producing abundant biomass for renewable energy production and the ability to sequester carbon both into the biomass and into the soil. It was found that in Western Europe alone SRC could annually sequester 24-29 tons CO_2 ha^{-1} (Deckmyn *et al.,* 2004). On average, SRC willow is able to sequester carbon at a rate of 3.00 Mg ha^{-1} y^{-1}, with 1.71, 1.25 and 0.04 Mg C ha^{-1} y^{-1} allocated to aboveground biomass, belowground biomass and into the soil to 60 cm depth (Lemus & Lal, 2005).

SRC crops undergo coppicing every 3-4 years which results in a multi-stem plant which can rapidly accumulate biomass and on average, these plantations have a life span of approximately 20 years. SRC crops are also advantageous because they require low inputs (fertilizer, pesticides, herbicides, water), they do not have many pests and are fairly lowly susceptible to disease. Short-rotation coppice and grass cultures are the most promising source of biomass at present (Rowe *et al.,* 2009) and have been shown to be the one of the most energy-efficient carbon conversion technologies to reduce greenhouse gas emissions (Styles & Jones, 2007), although there still remains limited experimental data to confirm this statement. They are also a preferred biomass crop over first generation food crops because they produce more biomass per hectare and unlike oilseed crops, the entire crop is utilized as a feedstock or to produce fuel. In order for bioenergy crops to present a solution for the future, they need to be both environmentally and energetically viable and outweigh the energy used in the harvest, transportation and production from the feedstocks. For example, when compared to coal, SRC willow is able to yield 36-times more energy than coal per unit of fossil energy input and simultaneously emit 24-times less GHG than coal (Djomo *et al.,* 2011). One review, of over 15 years of research concluded that the benefits of SRC willow were carbon sequestration into soils, reduced erosion, phytoremediation and lower SO_2 and NO_x emissions when biomass was co-fired with coal (Abrahamson *et al.,* 2002).

One of the major constraints with the application of energy from biomass is the land required to cultivate energy crops. Land use in the UK is particularly pressing with a population density of 256 people per km^2 versus the USA with only 34 people per km^2 (Office for National Statistics, 2011; United States Census Bureau, 2012). In many places in the world, any land that is fertile and able to grow food crops is likely already under cultivation, with bioenergy crops directly displacing food or fodder crops. This direct displacement is now considered to lead to consequential indirect effects (Indirect Land-Use Change – iLUC) where other land is required to grow additional food and where this may be high carbon, such as that from deforestation and other pristine areas. The impact of these indirect effects (Searchinger *et al.,* 2008), is yet to be fully resolved and is beyond the scope of this review.

However in developing sustainability criteria, the concept of iLUC factors, is being considered and it is likely that these factors may be twice the magnitude in some circumstances of the GHG costs through direct impacts assessed at a local level (Melillo *et al.,* 2009). These authors have suggested a global policy to protect forests and minimize the use of fertilizers (which may make the most significant contribution to overall GHG emissions), and would contribute towards the development of global sustainability criteria that take into account indirect effects most effectively. Fritsche *et al.* (2010) review the options for taking account of iLUC in policy development, and in their review, the CCC concludes that either crop-specific iLUC factors are included for the growth of specific feedstock crops or limits are placed on the use of feedstocks with iLUC risks (CCC, 2011). For the present, much emphasis is placed on the growth of energy crops on less fertile degraded land, areas of ex-set aside or along field margins, thus avoiding both direct and indirect land- use changes associated with food production.

Sources of biomass energy come in several forms: first generation bioenergy crops which are produced mainly from food crops such as grains, sugar beet and oil seeds; and second generation bioenergy crops which are dedicated lignocellulosic feedstocks such as short-rotation coppice, willow and poplar, and perennial grasses such as *Miscanthus* and (in the USA) switchgrass. Second generation bioenergy feedstocks can also include crop/forest residues, wood processing waste and solid municipal wastes. Third generation feedstocks are often defined as those from algal growing systems, either as macro-algae or micro-algae in bioreactors and open ponds, considered to have limited land-use implication for the UK; although their potential may be significant, these third generation feedstocks are considered beyond the scope of this study. These sources of biomass are summarised in Table 3.

	Crop Type	Source
Crops	First generation arable[1]	Wheat grain, oil seed rape, sugar beet
	Dedicated second generation[1]	SRC poplar and willow, *Miscanthus*
	Short rotation forestry[1]	Eucalyptus, Alder, Ash, Birch, Sycamore, Beech, Conifer
	Third generation algae	Micro-algae and macro-algae (seaweed)
Residues	Forestry	Wood chips, sawdust, bark, brashings
	Arable crop	Straw
Wastes	Wood	Contaminated wood waste
	Organic	Animal manures and sewage sludge, food and garden waste
	Landfill gas	Gas from land-fill sites

Table 3 - Main forms of biomass feedstock in the UK land system. [1] Indicates those crop transitions covered in this study.

Energy from biomass, in addition to enhancing energy security and supply, also has global social and environmental consequences that are wide-ranging and complex. These include the contribution of bioenergy chains to ecosystem services and here, the regulating service of greenhouse gas emissions and climate regulation is considered alongside the supporting services for biogeochemical cycling of carbon and other greenhouse gases, particularly N_2O. In the IEA (ETP, 2010) 'blue map' scenario – the scenario to achieve a GHG emissions reduction on 2005 emissions of 50% by 2050, with enhanced energy security, suggests that renewables will contribute 17% of the required reduction. Within this, biofuels meet 20% of total transport fuel demand and contribute to more than 30% of power generation from renewables by 2050. Without the 'blue map', the baseline scenario predicts that GHG emissions will double over the same timeframe, leading to a rise in temperature in excess of 2.4 ºC, considered unsustainable (IPCC, 2007). Thus, in a global context, the role of bioenergy in contributing to these important regulating and supporting ecosystem services is only just beginning to be considered, with limited empirical evidence on which to base assumptions. Of particular significance is the LUC, or crop transition that is associated with the bioenergy crop. Some transitions may provide no net benefits (e.g., one arable crop exchanged for another), whilst others may be positive transitions with improved GHG mitigation potential (e.g., an annual crop replaced with a perennial crop), Hillier *et al.,* (2009).

Land use and LUC both hold very large environmental implications including, but not limited to, reduced carbon stocks, soil quality, water quality and losses in biodiversity. Sala *et al.* (2000) found that LUC is the largest driver of biodiversity loss globally, closely followed by climate change. LUC was responsible for 6-17% of total anthropogenic GHG emission during the 1990s, equalling 5.9 Gt CO_2-eq y^{-1} (IPCC, 2001). In this review, LUC will be assessed in terms of its effects on soil organic carbon (SOC) and on greenhouse gas balance (GHG) during conversion to bioenergy cropping systems in the context of the UK. As well as LUC, in order to achieve a secure future for the production of bioenergy crops and to meet future global demands, increased yields and intensification are likely to be required. If we look at traditional arable farming, an increase in yield is accountable for ~80% of the increase in global agricultural commodity and the remaining ~20% is due to land expansion (see FAO, 2008). Technological advances in the machinery used to process feedstocks and convert biomass into useable forms of energy will need to be advanced to make the process as efficient as possible, as many of these techniques are far from optimised for relatively new bioenergy cropping systems. Integrated biorefineries - where production of food, feed and fuel can all happen under one roof - is a promising means to reduce the amount of waste produced from these processes and also reduce the transportation emissions from moving wastes to other factories to be processed. Though these factors are out of the scope of this review, they are important considerations that must be taken into account when making policy for future land-use and management.

3.1.1 Policies and obligations

The uncertainties surrounding the sustainability of biofuels (Scharlemann, 2008) has prompted a number of international initiatives to establish ‘sustainability criteria’ that propose frameworks and certification, to varying degrees to ensure bioenergy feedstocks are planted only when no significant negative impacts are apparent. These standards, and the assumptions that underlie them, are important, since in Europe, GHG emissions reduction are central to the development of current and future targets for cultivation within the EU and also for import of feedstocks and fuel. The research described in this review is central to the development of appropriate criteria, since many rely on modelled data and look-up tables from which to extract the GHG balance data for different cropping systems. This presents considerable uncertainty to policy development since few empirical data are available from which to verify figures used in LCA and other sustainability criteria, and these are prone to errors (Whitaker *et al.,* 2009; Rowe *et al.,* 2011). These international initiatives are summarised in Table 4 and include a mixture of groups with statutory responsibilities (such as Government Departments, EU), trade organisations (with profit and commercial priorities), NGOs, scientists and other international organisations such as FAO, OECD and World Bank.

Initiative	Overview of activity in sustainability	Relevance to the UK
Better sugar cane initiative	Sugar cane retailers, investors and traders NGOS to create standards for sustainable sugarcane cultivation	None to ELUM
Global Bioenergy Partnership	G8 + 5 initiative (Brazil, China, India, Mexico and south Africa). Rules and tools for sustainable bioenergy. Taskforce on sustainability and GHG methodology, considering social, environmental and economic indicators	Yes, GHG indicators are part of the framework, including lifecycle GHG emissions
Green Gold label	Established in 2002 by Dutch Energy company, Essent and Skall International. Certified over 25 companies as delivering sustainable biofuels	None to ELUM
IEA task 40	Sustainable international bioenergy trade, supported by Belgium, Canada, Finland, Germany, The Netherlands, Norway, Sweden, UK.	None to ELUM, since considering the UK system and not imports
Round Table on Responsible Soy Association	A multi-stakeholder initiative to facilitate a global dialogue on soy production that is economically viable, socially equitable and environmentally sound. Version 1 of Standards is published	None to ELUM since Soy is not a UK crop
Roundtable on Sustainable Biofuels	A Multi-stakeholder group to develop standards for the sustainability of biofuels. An initiative of the Swiaa Ecole Polytechnique Federale de Laussanne. The goal is to create a sustainability certificate, approved in 2009. Essentially a GHG balance calculator	Yes but difficult to access
Roundtable on Sustainable	RSPO aims to promote the sustainability of the entire palm oil chain, largely driven by	No. Limited imports of palm oil to UK and very generic

Palm Oil	industry in discussion with stakeholders	sustainability criteria
European Union	EU Renewable Energy Directive (RED)	Adopted in April 2009 (Directive 2009/28/EC), to achieve a 20% share of energy from renewable sources. GHG calculation impacts of biofuels and carbon stocks changes, using national GHG inventories. IPCC tier 1 methodology agreed. Land with high carbon stocks, biodiversity ruled out. This is currently a voluntary scheme. GHG emissions saving of 35 % (rising to 50% Jan 2017) and 60% in Jan 2018).

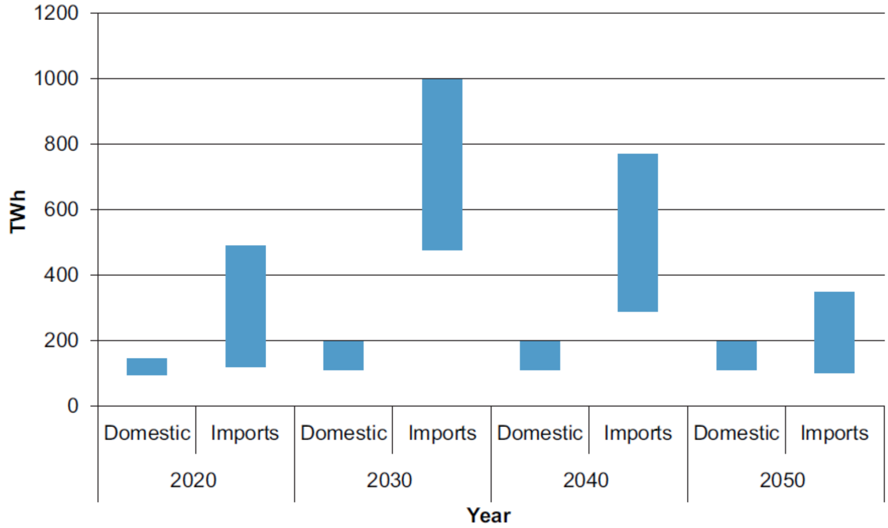
Table 4 - Overview of Bioenergy Sustainability Initiatives

The EU (as part of RED) is currently dedicated to increasing the amount of renewable energy used to 20% of total energy consumption by 2020 whilst simultaneously reducing GHG by 20% by 2020 (European Commission, 2009). Currently in the EU, around 3% (3.1 Mha) of EU croplands is used for bioenergy, supplying 7% of the total primary energy (IEA, 2010; EU, 2007). In the UK, crops occupy 77% of the total UK agricultural land area (DEFRA, 2007), and of this only 0.01 Mha is bioenergy crops under cultivation (UK Bioenergy Strategy, 2012). For first generation crops however, it is less clear how much contributes to bioenergy, for example Oil Seed Rape (OSR) covers 43% of arable land in the UK and is used for both food and biofuel, but it is unclear how much is dedicated to each use (DEFRA, 2007); according to the Renewable Transport Fuels Obligation (RTFO) quarterly report, approximately 3% of all UK cereals were used to produce biofuels in 2009 (RTFO, 2010).

The UK Bioenergy Strategy (2012) is based on 4 principles:

1) Policies that support bioenergy should deliver genuine carbon reductions;
2) Support for bioenergy should make a cost effective contribution to UK carbon emissions objectives;
3) Support for bioenergy should aim to maximise overall benefit and minimise cost across the economy;
4) Policy makers should assess and respond to the impacts of increased deployment.

Through the 2009 Renewable Energy Directive, the UK should have 15% of all energy from renewable sources by 2020 and to reduce GHG emissions by at least 34% by 2020 and 80% by 2050, as enforced by the Climate Change Act 2008 (emissions from a 1990s baseline). Currently bioenergy provides 3% of the total UK energy consumption, with 65% of this from electricity generation (UK Bioenergy Strategy, 2012). An analysis undertaken as part of the recent UK Bioenergy Strategy projects that sustainably sourced biomass will contribute 8-11% and 8-21% of the total energy by 2020 and 2050, respectively. One estimate predicts that in order to be able to meet the UK strategy, 350,000 ha of land will need to be under perennial crop cultivation, requiring an increase of over 2000% in area from only 15,000 ha grown in 2008 (Karp *et al.,* 2009), which had risen to approximately 19,000 ha for 2009/2010 (see Don *et al.,* 2012). The UK Bioenergy Strategy (2012) estimates the theoretical maximum area available to cultivate SRC willow and *Miscanthus* is estimated at between 0.93 - 3.63 Mha in England and Wales. It is clear from these and other studies, that in order to reach sustainability targets for 2020 and for 2050, the UK will need to supplement its own biomass with that from international imports (AEA, 2011; Figure 3). The equivalent amount of land required globally to supply the UK has been projected as 0.6-2.2, 0.04-2.6 and 3.7-17.2 Mha for agricultural residues, oil crops and woody biomass, respectively (UK Bioenergy Strategy, 2012). Within this requirement, it is critical that UK-sourced biomass is grown in a sustainable manner. Whilst this review aims to focus explicitly on the UK system boundary, there will be global impacts on adoption of bioenergy crops in the UK. For instance, if we are able to optimise the production of UK-sourced biomass feedstocks, this reduces the global impact on international imports, for example, in areas of the topics where native tropical forest is being removed for bioenergy crop production. Brazil and Indonesia are responsible for 61% of global CO_2 emissions from LUC (Le Quere *et al.,* 2009), although the contribution of bioenergy cropping to this figure is likely to be small. Presently, the largest UK import of biofuel is Argentinian supplied soy-based diesel (DECC), although this may change with increased production of Brazilian ethanol in future.



Source: DECC analysis based on AEA Biomass resource model

Figure 3 - Amount of energy provided from biomass supplied from domestic and international supplies (from UK Bioenergy Strategy, 2012)

Set-aside is land which is prevented from being cultivated on farms across Europe, and was introduced in 1992 as part of the Common Agricultural Policy (CAP). Previously this was obligatory and was a percentage of the total land a farmer had in cultivation; however, as of 2007 it became voluntary to participate and it was completely removed from the CAP in 2008. The purpose of set-aside was to prevent over-production on farms and to help avoid negative environmental impacts on the soil and on the landscape. After the set-aside initiative came to an end, as much as 20% of land in the EU was immediately re-entered into cultivation (Don *et al.,* 2012). In the UK some of the land was also redistributed into the Environmental Stewardship scheme, another governmental incentive to protect the landscape where famers are paid not to cultivate land. It is these lands which have the potential to be converted into bioenergy crops in the future, to avoid cultivation on fertile lands and therefore direct competition with food production. However, currently they are excluded from Energy Stewardship Scheme (ESS): if payment is received for ESS it cannot be received from the Energy Crops Scheme.

It is important that there is a reliable and rigorous means of measuring LUC when considering land conversions to bioenergy crops. At present, the IPCC present a standard method for estimating SOC stock based on land-use and management, measured at three tiers, depending on the data collected for that area. However, there are fundamental flaws in the system, requiring further development and implementation so that LUC decisions can be better informed for conversions like that to bioenergy crops (Smith *et al.,* 2012). Another policy issue highlighted by Gallardo and Bond (2011) is that in UK there is no legal mandate for conducting assessment for LUC to bioenergy crops (except for rare cases where protected lands are involved), therefore highlighting the fact that more could be done at a governmental level to help protect the environment.

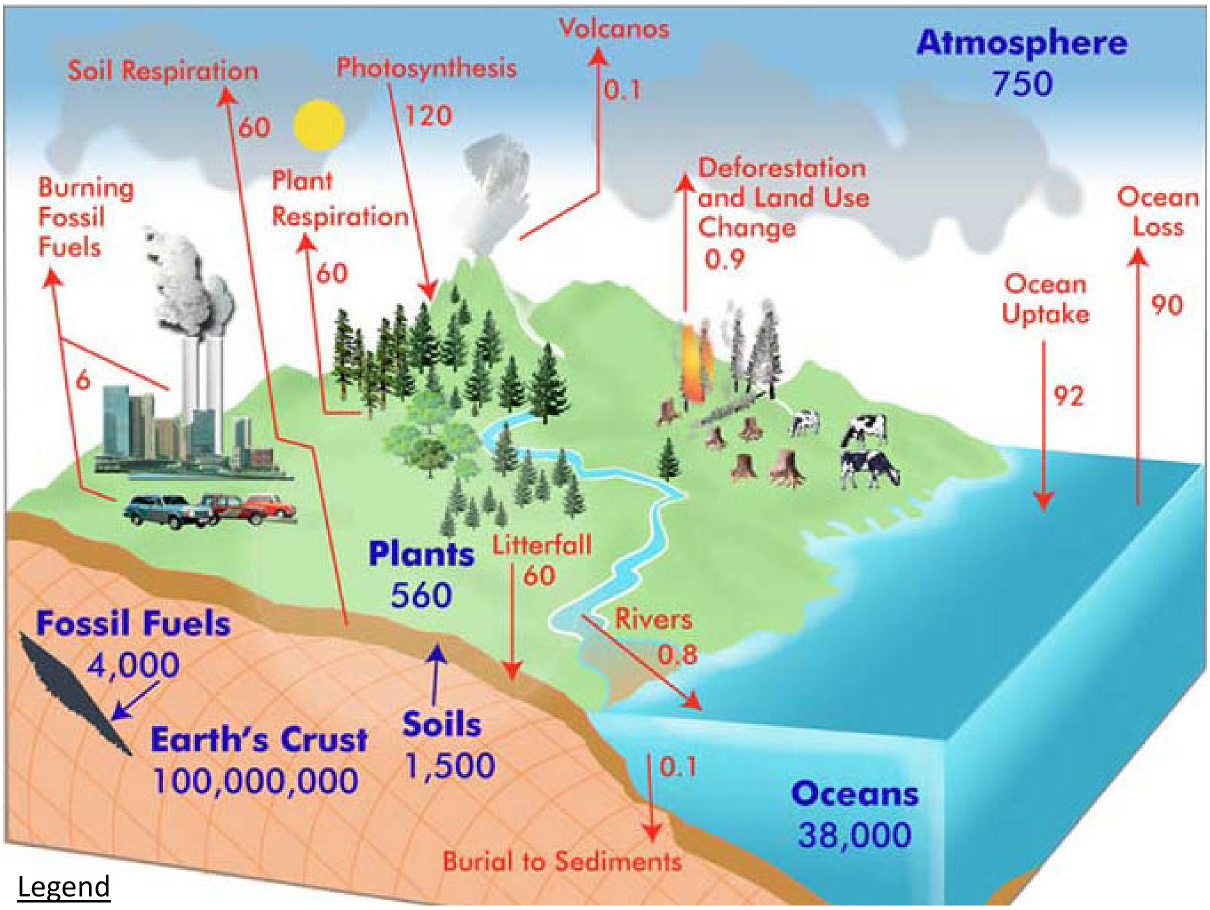
3.1.2 The importance of the soil for GHG mitigation in land use transitions to bioenergy

The soil is extremely important in the global carbon cycle as it holds 1500 PgC (equivalent to 1500 billion tonnes), which is more than the vegetation and atmosphere are able to hold together (Fig 4), presenting the largest terrestrial stock of carbon. Lal (2004) highlights the importance of SOC for its on-site and off-site values to our landscape and to human well-being (Table 5). SOC is considered as any organic input from plant, animal or microbial matter which is at any stage of decomposition. The amount of carbon fixed into the soil is the balance between the rate of inputs, in this case from litter for example, and the mineralization of the existing soil carbon stores (Jenkinson, 1988; Post & Kwon, 2000). The global carbon pool is made up of 5 main pools as shown in Figure 5; these all play a part in CO_2 efflux from the soil but only 'SOM-derived CO_2' significantly contributes to changes in atmospheric CO_2 concentration (Kuzyakov, 2006). It is important to be able to measure the different sources of CO_2 efflux from each of the different pools, as this allows us to evaluate whether the soil is acting as source or a sink for CO_2; this can be found in a comprehensive review of partitioning methods by Kuzyakov (2006). The soil is not an unlimited sink, and has a limited carbon storage capacity which is determined by vegetation type, climate, nutrient content, hydrology and topography (Gupta & Rao, 1994; Nair *et al.,* 2009). Anthropogenic activities such as LUC and land management have extremely large impacts on the soil carbon pool, resulting in increased emission of CO_2 due to decomposition of SOM or increased soil respiration (Schlesinger , 2000).

Soil functioning underpins ecosystem services and is important to consider when discussing the effects of LUC, although few studies have considered processes such as predation in bioenergy systems. In a comprehensive review by Baum *et al.* (2009), it was found that land conversions to SRC willow and poplar can have both positive effects (such as increased abundance of earthworms and positive effects on nutrient cycling), as well as negative effects (such as dominance of arbuscular mycorrhizal host plants). Rowe *et al.* (2012, in press) have also considered ecosystem functioning alongside biodiversity and report significant increases in predator abundance and altered decomposition rates in SRC willow compared to arable crops.

On-site benefits of SOC	Off-site benefits of SOC
Source and sink of principle plant nutrients	Reduced sediment loads in streams and rivers
Source of charge density and responsible for ion exchange	Filters pollutants from agricultural chemicals
Able to absorb water at low moisture potential thereby increasing plant available water capacity	Aids biodegradation of contaminants
Promotes soil aggregation which improves soil tilth	Buffers GHG emissions from soils into the atmosphere
Caused high water infiltration capacity & low losses due to surface runoff	
Substrate for soil microbial communities therefore increase biodiversity	
Provides strength to soil aggregates leading to a reduction in erosion susceptibility	
Encourages high nutrient and water use due to reduced losses by drainage, evaporation and volatilization	
Buffers against pH fluctuations due to addition of agricultural chemicals	
Moderates soil temp through effect on soil colour and albedo	

Table 5 - Onsite and offsite benefits of SOC on the landscape (From Lal, 2004)



Legend
Pools shown in blue (Pg)
Fluxes shown in red (Pg y^{-1})
Units: Pg = 10^{15} gC

Figure 4 - The global carbon cycle showing where carbon can be stored in pools or where it is released as fluxes (Adapted from http://globecarboncycle.unh.edu/diagram.shtml)

3.1.3 Initial conversion considerations

The initial conversion process from one land-use to another usually results in a release of emissions due to the removal of the current crop cover (either manually, with fire, or by chemicals), preparation of the land for planting (chemical and mechanical) and then the crop establishment phase (chemical). *Miscanthus* propagation in particular is known to be energy and GHG-intensive during the first stage of crop establishment (Styles & Jones, 2007). In a conversion from arable to SRC poplar, Arevalo *et al.* (2011) found initially a release of carbon occurred, but the soil had become a net sink by year two. The point at which the newly established land-use is equal to that of the previous land-use is sometimes referred to

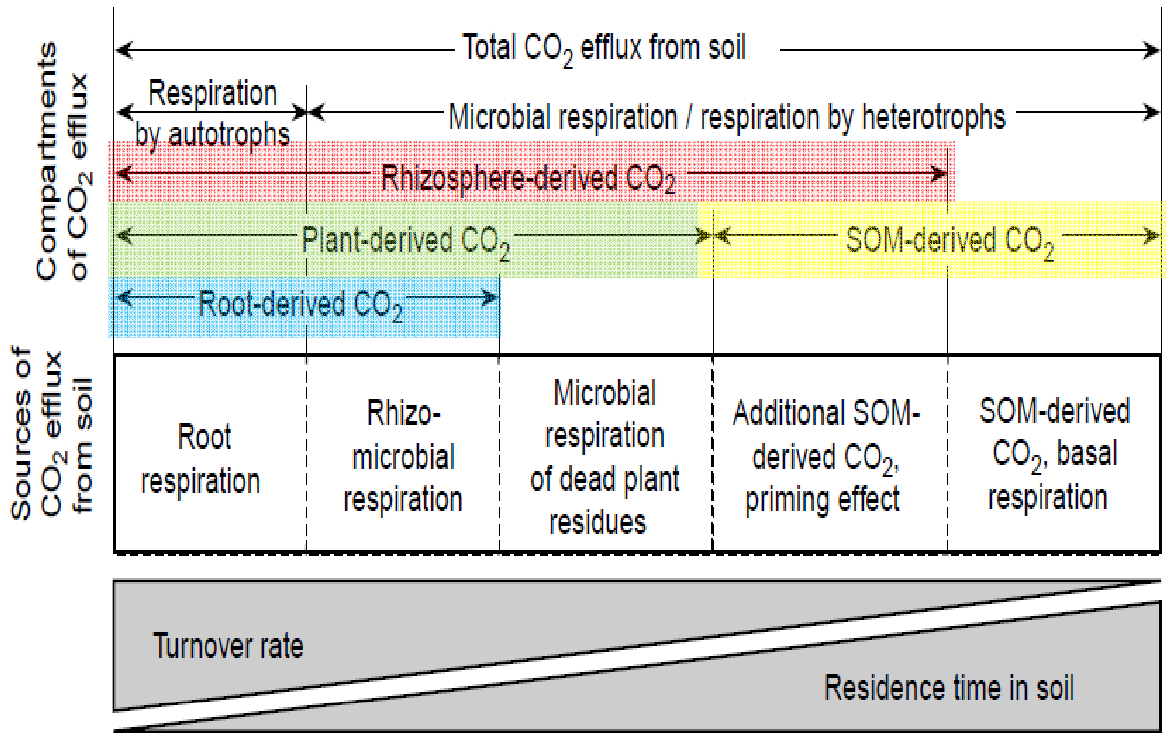


Figure 5 - Soruces of biogenic CO_2 efflux from soil in order of turnover rates and mean residence times in the soil (Adapted from Kuzyakov, 2006).

as the 'break-even point' or 'carbon neutrality' – in this particular study for arable to SRC poplar it was found to be 4 years, similar to other studies for this type of conversion (Price *et al.,* 2009). The first year of cultivation has been highlighted as a particularly sensitive year with respect to carbon balance. Data from a clustered eddy covariance approach shows how large carbon imbalances can be invoked, but also how a conversion to bioenergy can help stabilize and negate emissions in the long term (Zenone *et al.,* 2011). Abbasi & Abbasi (2010) are careful to point out that while bioenergy crops are considered 'carbon neutral', they are not necessarily 'nutrient neutral' as each crop will exert varying amounts of pressure on the nutrients of the soil on which they are cultivated.

Another study looking at the effects of the first year after establishment found that a conversion from arable land to SRC willow and poplar incurred a GHG debt of 7.4 and 11.6 Mg ha^{-1} y^{-1}, showing that while CO_2 emissions were 29-42% less than arable, the amount of N_2O emissions and nitrate leaching increased in the SRC plots (Nikiema *et al.,* 2012). This highlights the importance of taking into account all the effects of a conversion, showing how critical the first year can be in determining GHG savings; in the long term however, these debts should be repaid and the overall environmental gain should be greater than if no conversion was to occur. Styles and Jones (2007) found that while the conversion from de-stocked grassland to bioenergy crops would create a small increase in GHG emissions during cultivation, these would be greatly offset by their displacement of traditional fossil fuel use, a full LCA showing almost a 90% decrease in GHG emissions.

The initial land-use, management and fertilizer regime are the main factors in determining whether a conversion to bioenergy crops will be beneficial or detrimental, and also the conversion crop type (e.g., Tolbert *et al.,* 2002; Morris *et al.,* 2010). For liquid transport fuels, first generation crops OSR and wheat are primarily cultivated (Gallardo & Bond, 2011), which are annual row crops. Most annual cropping systems are associated with lower SOC contents than perennial crops and therefore these losses incurred (mainly by harvesting, ground preparation practices and removal of residues) need to be compensated by other management practices such as fertilizer of winter cover crops (discussed later in section 3.2). In a comparison between the effects of growing OSR versus *Miscanthus* and SRC willow, it was shown that OSR not only has detrimental effects on soil quality with decreased amounts of SOC during occupation but also had the highest acidification and eutrophication potentials (Brandao *et al.,* 2011). This study highlights the need to understand the full array of consequences of land-use and also how differing management strategies impact of the life cycle of various crops, i.e., the use of fertilizer for OSR cultivation (See Fig 6).

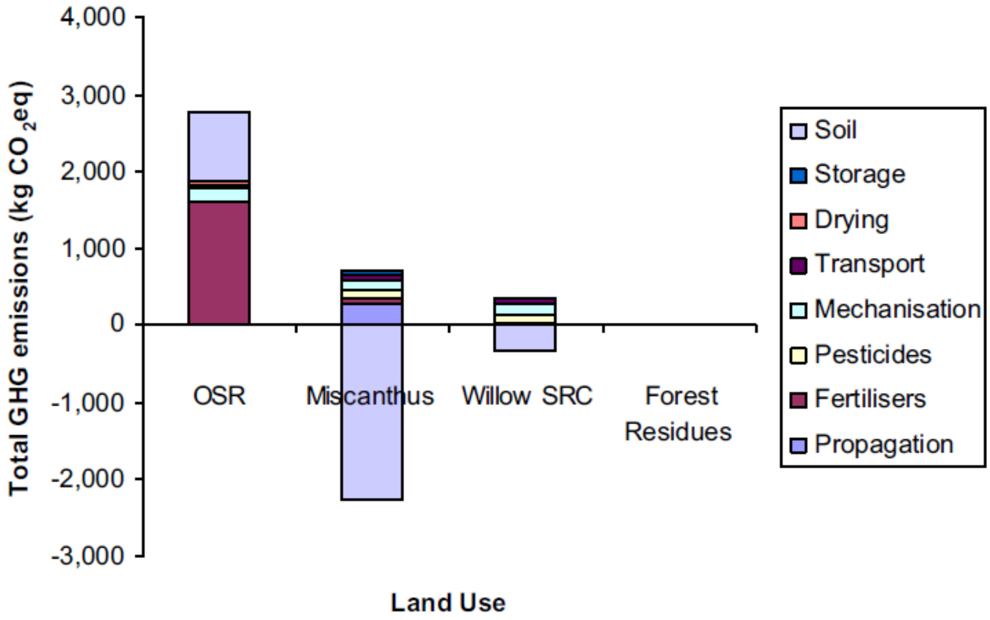


Figure 6 - GHG emissions of different land uses broken down into contributing factors, expressed per reference unit (ha-1 yr-1) (from Brandao *et al.,* 2011)

3.2 General LUC – Impacts on Soil Carbon

When discussing the effect of LUC on soil carbon stocks, it seems the most appropriate place to start is with the classic review by Gou and Gifford (2002). Gou and Gifford (2002) conducted a meta-analysis to quantify the effect of LUCs on soil carbon stocks and their results are summarised in Table 6. It is clear from this analysis that a conversion to croplands is detrimental and any conversion out of a cropland system causes an increase in soil carbon stocks – this is likely due to vast differences in management practices. The main take-home message from this paper, and a wealth of others in the published literature, is generally that a conversion away from the native land-use tends to have a negative effect on carbon stocks (e.g., Fargione *et al.,* 2008). It is not to say, however, that these changes are permanent, as these time-series are limited. One benefit of this review is that it considered soil depth in some detail and given the literature on tillage (see below), it is likely that this may impact the potential for bioenergy cropping systems to lead to improved soil carbon. In the current meta-analysis, soil depth is captured as a measurement variable wherever possible.

Original Land use	Transition to:	Effect on soil carbon stocks
Pasture	Plantation	-10%

Native forest	Plantation	-13%
Native forest	Crop	-42%
Pasture	Crop	-59%
Native forest	Pasture	+8%
Crop	Plantation	+18%
Crop	Pasture	+19%
Crop	Secondary forest	+53%

Table 6 - Summary of the findings from Gou and Gifford (2002) who conducted a meta-analysis to assess the effects of LUC on soil carbon stocks.

The ‘carbon debt’ or ‘carbon neutrality’ is a measure of the extent to which the use of bioenergy is able to reduce carbon emissions relative to a fossil fuel reference system. This is most often reported as an amount of years which will be required for the land conversion to be able to ‘pay back’ the carbon debt to the land. For example, in a study by Fargione *et al.* (2008), it was shown that in a conversion from US grassland to corn for bioethanol would incur a carbon debt of 93 years, and from abandoned cropland to corn, a 48 year carbon debt. This again presents another example where a conversion from a native ecosystem leads to more negative environmental impacts than a conversion from an already anthropogenically altered ecosystem. Another more worrying estimate was one of a conversion to corn, again in the USA, presenting a 167 year payback time, when indirect effects on land-use were also considered (Searchinger *et al.,* 2008). Failure of studies to take into account the effects of LUCs (both direct and indirect) will give an incorrect picture of the effects of a conversion to bioenergy crops and needs to be incorporated into all studies considering land conversions (Searchinger *et al.,* 2008; Fargione *et al.,* 2008).

Soil methane (CH_4) fluxes are often not discussed in many papers due to the fluxes being very small in relation to CO_2, but they are still an important component in the GHG balance of bioenergy crops. The soil acts as an important biological sink for CH_4, fixed by oxidation by methanotropic bacteria in aerobic soils; however in anaerobic environments methanogenic bacteria dominate, resulting in an emission of CH_4 (see refs within Kern *et al.,* 2012). In a comparison between annual and perennial bioenergy crops, it was found that in fact annual crops consumed more CH_4, 6.1 µg CH_4 m^{-2} ha^{-1} versus 4.3 µg CH_4 m^{-2} ha^{-1} for perennial bioenergy crops; it appears that soil water content is the main reason this difference is seen (Kern *et al.,* 2012). Thus far it has been found that perennial crops have a far greater environmental advantage over first generation annual crops, however in the case of CH_4 emissions annual crops seem to come up ahead in this case. The overall GHG balance can be supplemented by the fact that CH_4 is taken; Kern et al. (2012) predicted that 3-4% of CO_2-eq from soil borne N_2O emissions can be compensated by the consumption of methane in this experiment.

3.2.1 Specific crop transitions of relevance to the UK

3.2.1.1 Transition from arable to bioenergy crops

Several studies have investigated the effects of a conversion from traditional annual, arable to perennial bioenergy crops. The general consensus is that this conversion to SRC and *Miscanthus* results in increased SOC and soil quality (e.g. Tolbert *et al.,* 2002; Anderson-Teixeira *et al.,* 2009). However, care should be taken in assessing the results since many rely on modelled and not measured data, and when measured studies are undertaken, often only the top 30 cm soil profile is investigated. In an analysis of the literature, Harrison *et al.* (2011) have concluded that this can lead to erroneous conclusions, and caution against shallow soil sampling in studies to quantify soil C pools and changes in soil C over time. New data are now emerging such as Gauder *et al.* (2012), who have measured GHG flux across willow SRC, *Miscanthus* and maize at two levels of fertilizer, and show fluxes of these gases to be greatest from fertilised maize, but no data as yet are available for SOC. It's likely that these studies over the long-term will provide more conclusive data to address this question.

Future research should be focused on long-term measurement campaigns with field-grown trees and grasses, in controlled replicated studies to ensure the evidence base to assess changes in soil carbon in firm and UK-specific

Future research should target resources for long-term soil-based studies that include the whole soil profile down to 1 m

The UK Bioenergy Strategy (2012) found that the energy balance of dedicated biomass crops can have lower direct carbon impacts between 0.5 – 6.1 t CO_2-eq ha^{-1} y^{-1}, than food production 3.4 – 11 t CO_2-eq ha^{-1} y^{-1}. The detrimental impacts of arable lands have been highlighted in several studies; one study found that if 50% of the area in the EU which is currently planted with silage maize is replaced by permanent grass or temporary grass, GHG emissions would be reduced by 1.3 Mt CO_2-eq ha^{-1} y^{-1} and 0.9 Mt CO_2-eq ha^{-1} y^{-1} (Henriksen *et al.,* 2011). The complete conversion of arable land to permanent grass is estimated to increase soil carbon by 0.5 t ha^{-1} y^{-1} (IPCC, 2001; Conant *et al.,* 2001). In terms of SOM, annual crops to SRC results in an average SOM increase of 1 t C ha^{-1} y^{-1}; yield increases due to every additional tonne in SOM are approximately 5% (see refs within Nijsen *et al.,* 2012). These carbon gains from conversion are likely mainly due to the change in management practice, particularly no-tillage, thereby highlighting the vast impact management can have on carbon balance (See section 3.2).

A comparison between fields under two different land uses (space for time comparisons) is one method to investigate the experimental effects. In one study where arable OSR and wheat were compared to SRC willow and *Miscanthus*, it was shown that the main difference was the N_2O fluxes were significantly smaller for bioenergy crops than arable crops (Drewer *et al.,* 2012), but this effect was reversed when fertiliser was added to the perennial bioenergy crops in both *Miscanthus* and SRC; this suggested that the GHG mitigation potential of crop transitions from arable to perennial crops is highly dependent on fertiliser regime. In a review by Anderson-Teixeira *et al.* (2009), it was shown that upon conversion to perennial species the average SOC accumulation rate was <1 Mg C ha^{-1} y^{-1} in the top 30 cm of soil. Similar data were reported in a review by Don *et al.,* (2012), with 0.44 Mg soil C ha^{-1} y^{-1} for poplar and willow and 0.66 Mg soil C ha^{-1} y^{-1} for *Miscanthus*. For switchgrass, up to 1.1 Mg soil C ha^{-1} y^{-1} was reported (Monti *et al.,* 2012). These changes are likely attributable to a change in management practice and changes to soil properties by the crop cultivated; for example a switch to a “no-tillage regime” results in less exposure of SOM and therefore decreased decomposition, but this may be complicated at depth in the profile and this is often not fully investigated in approximately 50% of the studies reported by Anderson-Teixeira et al (2009).

The consensus of evidence available suggests that transitions from annual arable to perennial grass and SRC crops leads to improved SOC, but the overall GHG balance to farm-gate may be positive or negative and largely driven by fertilizer input and consequent N_2O emissions. Accumulation of SOC is in the range 0.44-1.1 Mg C ha^{-1} y^{-1}.

The cultivation of perennial crops helps to stabilize the soil after a conversion by allowing the soil to accumulate into macro-aggregates, thereby allowing the sequestration of more organic carbon (Grandy & Robertson, 2007). Perennial crops are also able to provide benefits through their deeper and more extensive rooting system, providing both physical stability and chemical stability through the presence of mycorrhizal fungi in symbiosis with roots. Godbold *et al.* (2006) illustrated in a FACE carbon labelling experiment using poplar

SRC that movement of carbon into the SOM pool was predominantly via the mycorrhizal external mycelium, exceeding the input from leaf litter and fine root turnover.

The benefits of a conversion to SRC cultivars for energy have been quantified in other studies as an economic value which represents the savings that will be made as a result of the LUC; for example Updegradd *et al.* (2004) found a saving due to carbon sequestration of \$13-15 ha^{-1} over a 5-year rotation period for SRC poplar when used as a bioenergy crop. More recently Valentine *et al.,* (2011) have extended this and placed a value of \$56-218 bn per annum for the carbon emissions savings, globally, given the price of carbon at \$40 per tonne.

3.2.1.2 Transition from Degraded, Marginal and Abandoned Land to Bioenergy Crops

It has been suggested that the indirect impacts of increased bioenergy crop deployment globally, could be largely mitigated if energy crops are planted on degraded and abandoned land that does not provide any provisioning ecosystem services (Gallagher, 2008). The problem with this approach is two-fold. Firstly, such areas may provide significant 'other' ecosystem services related to biodiversity and amenity that may be enhanced or lost with transition to bioenergy crops. Secondly, considerably lower crop yields are likely from such land. The total global area of degraded land has been estimated in several recent studies, with varying results. Nijsen *et al.* (2012) gave a figure of 1836 Mha, with less than 6% of this in the EU (Nijsen *et al.,* 2012). A study based on satellite and historic data suggested an abandoned agricultural land resource between 385-472 million hectares (Campbell *et al.,* 2008), with a mean bioenergy crop yield of 4.3 tons ha^{-1} y^{-1}. Cai *et al.,* (2010) estimated marginal agricultural land at 320-702 Mha (increasing to 1411 Mha if grassland savannah and shrubland with marginal productivity were included), with a suggestion that Africa and Brazil together have more than half of the total marginal land available for bioenergy crop production. This further emphasises the likely requirement of Europe to seek imported feedstock resources in future, where sustainability standards are difficult to control. Globally, the main causes of soil degradation are deforestation (29.4%), overgrazing (34.5%), and intensive agriculture (28.1%) (Oldeman, 1994; Lemus & Lal, 2005). Growing any crop on marginal, degraded or poor quality lands will result in lower yields due to lower levels of water and nutrients. Simulations performed by Nijsen et al. (2012) showed that woody crops (SRC willow and poplar) and grass species (switch grass and *Miscanthus*) yielded 8.9 and 6.8 odt ha^{-1} y^{-1} odt on degraded lands respectively; Campbell *et al.* (2008) suggest 4.3 tonnes ha^{-1} y^{-1}. These projected yields are lower when compared to the latest available varieties in the UK at 6.71 – 12.3 odt ha^{-1} y^{-1} and 12-16 odt ha^{-1} y^{-1} for SRC willow and *Miscanthus* respectively (Macalpine *et al.,* 2011; Natural England, 2007). This suggests that breeding targets in future should focus on breeding for optimum, rather than maximum, yields with limited inputs of fertilizer and water (Sims, *et al.,* 2006; Karp and Shield, 2008).

The type and the severity of the degradation will determine the amount of yield losses, varying between 4.6 - 88% yield reductions (Nijsen *et al.,* 2012). Such losses however may not be permanent due to the positive effects of planting SRC and *Miscanthus* on the land. These crops are able to significantly increase the productivity of the landscape by increasing soil stability through rooting structures, increased SOM through residue/litter fall and increased biodiversity (e.g. Rowe *et al.,* 2010). SRC willow and poplar are known for their ability to grow on poor quality lands and for their phytoremediation capacity, making them well suited to cultivation on marginal and degraded lands (e.g. Doty, 2008; Baum *et al.,* 2009).

Several different estimations have been given for the potential of growing energy crops on degraded lands (Table 7); on average, together they predict a potential between 4.2 – 24.2 EJ Mha^{-1} y^{-1}, irrespective of yield and therefore variable depending on crop and level of degradation.

Area of degraded land (Mha)	Bioenergy Potential (EJ y^{-1})	Yield (Mg ha^{-1} y^{-1})	Reference
430 - 580	8 - 110	1 – 10	Hoogwijk et al. (2003)
500	45	4.5	Tilman et al. (2006)
550	43	-	Van Vuuren et al. (2009)
1836	151 - 193	6.8 – 8.9	Nijsen et al. (2012)

Table 7 - Global energy potential for the production of bioenergy on degraded lands

In the context of this review and a system-bound UK, agricultural land classes (ALCs) may be used to identify areas of low productivity and these have been linked to other land constraints including national parks, pristine high-carbon soils and land with high biodiversity value in Sites of Special Scientific Interest. Using this constraint mapping approach, estimates of biomass supply have been made for both SRC and *Miscanthus*. Lovatt reported that between 4-28% low quality agricultural land would be required to supply 350,000 ha *Miscanthus*, with a total production of 4.56 Modt from England that would enable 2.4% of total energy demand to be met - just from plantings in very poor agricultural land. Similarly for SRC in England, Aylott *et al.,* (2010) showed that 7.5 Modt was realistically available for England, requiring growth on 800,000 ha of poor-quality land, supplying 4% of current electricity demand. Research is currently in progress to identify how these two crop types will act together, since in general, SRC yields better in the westerly areas of the UK, whilst *Miscanthus* shows preference for the south and east (Bauen *et al.,* 2010); this has also been confirmed by more recent work (Tallis *et al.,* 2012) and within the ETI (BVCM research project; Richter *et al.,* data unpublished; Taylor *et al.,,* data unpublished).

Others have also investigated mass scale afforestation on degraded or poor-quality land with SRC cultures; for example in a modelling study in Canada, afforestation with SRC willow over 2.12 Mha of marginal land in Saskatchewan showed sequestration rates of 5.7-7.5 Mg C ha^{-1} y- over a 44 year simulation (Amichev *et al.,* 2012). The importance of taking into account the quality of the land can be seen when comparing a grassland to degraded grassland; for example, conversion from a grassland to corn caused an emission of 79 gCO_2/MJ whereas a conversion from degraded grassland sequestered 11 gCO_2/MJ (Lange, 2011). Beringer *et al.* (2011) warns that if biomass cultivation is not restricted to abandoned or marginal lands, the spatial expansion will put already vulnerable ecosystems at further risk.

3.2.1.3 Transition from grassland to bioenergy crops

Improved grasslands are important sources of terrestrial carbon storage, holding the second largest store after bogs, with approximately 274 million tonnes of carbon (Ostle *et al.,* 2009). It has been shown that a conversion of arable to permanent grass will increase soil carbon by 0.5 t ha^{-1} y^{-1} (IPCC, 2001; Conant *et al.,* 2001). Ostle *et al.* (2009) found that the single largest contributor to soil carbon losses due to LUC was the conversion from improved grassland to arable crops, between 1990 and 2000 in the UK. In the UK context, conversion of semi-permanent, permanent or managed grassland to bioenergy cropping systems probably represents one of the most controversial land-use transitions, since grassland is a significant part of the UK landscape (4-5 Mha, DEFRA, 2007) and because management of different grasslands can vary widely in the UK, particularly with respect to fertiliser input and grazing. This can have a dramatic impact on the GHG benefit or cost on transition to either first, or second generation bioenergy cropping systems. St Clair *et al.,* (2008) and later refined by Hillier *et al.* (2009) provides the most comprehensive UK-centric data set, used in the recent CCC review (2009). Here the results are clear (Figure 7): transition from grassland to first generation energy crops results in a net loss of C eq, from the system whilst transition to second generation crop provides a net benefit. However, these data represent modelled outputs only, with limited validation. Consideration of limited, but increasing, field data sets from long-term studies provides no clear picture on the likely consequences of grassland conversion.

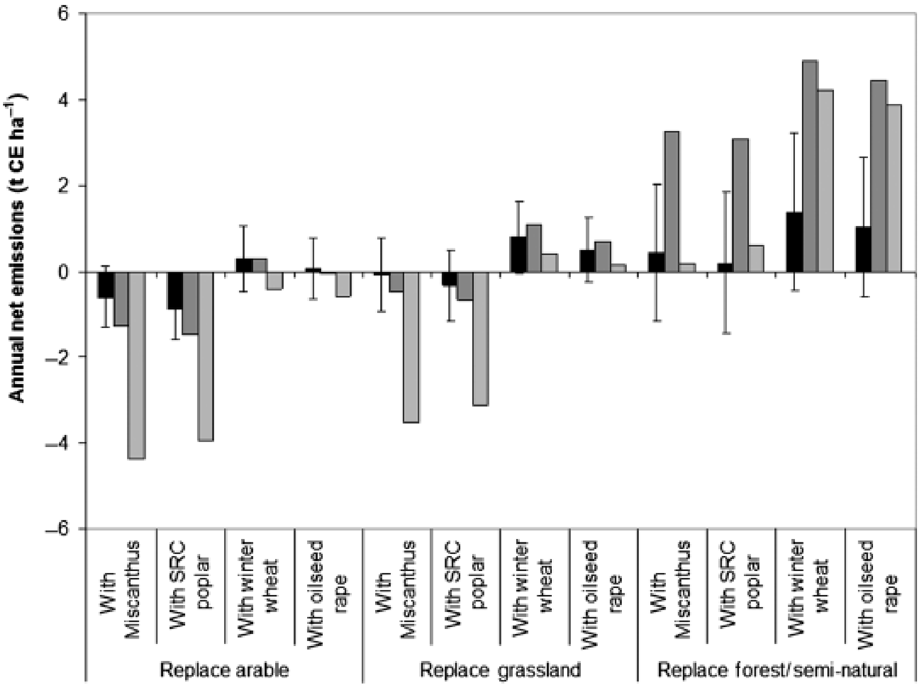


Figure 7 - Taken from Hillier *et al.,* (2009). Net annual gas (t CE ha^{-1}, CE = carbon equivalents) balance for all replacement scenarios, arable, grassland and forest/semi-natural, with bioenergy in the UK. Black – soil emissions, grey – incorporating before and after management emissions, light grey – incorporating fossil fuel substitutions. Error bars represent ± 2 SD.

In one report, long-term below-ground storage of carbon by bioenergy crops has been shown to be equal to or greater than that of grasslands due to the long rotation and extensive fine roots of SRC crops and the rhizome mass of *Miscanthus* (see refs within Style & Jones, 2007). However, recent work by Zimmermann *et al.* (2012) in a comparison of *Miscanthus* and tillage grassland at 16 sites following conversion in 2006, showed no significant improvement in SOC, when sampled after 2-3 years, post-conversion. However, for a switchgrass modelling study that considered 12 simulation scenarios, a net C sequestration was observed in 11 out of 12 simulations, as determined by amount of nitrogen fertilisation and initial soil carbon stocks; this makes generalisations difficult (Garten, 2012). Again, these are modelled data with few empirical studies available. Monti *et al.* (2011) confirmed both positive and negative changes in soil C for switchgrass, but in a modelling exercise by Anderson-Teixeira et al. (2009), grassland conversion to either *Miscanthus* or switchgrass resulted in a net increase in SOC, with the largest effects seen in switchgrass.

The GHG benefit of conversion from grassland to second generation cropping systems remains uncertain due to limited empirical data and mis-match between modelling and measurement reports.

Conversion of grassland to first generation crops appears to provide a more robust dataset. Conversion to soybean from unmanaged grassland and arable lands have been compared and it was shown that there are greater benefits from converting from arable lands as there is a lower soil quality and lower initial carbon stocks (Bhardwaj *et al.,* 2011). In Europe, the conversion from set-aside grassland and improved grassland to oil seed rape has been shown to sequester 0.6–3.3, and 2.2–10.6 t CO_2-eq ha^{-1} y^{-1}, respectively (Flynn *et al.,* 2012). Smeets *et al.* (2009) in a modelling study reported reduced GHG balance of sugar beet, oil seed rape and wheat relative to a grassland control, although most of the study was considering N_2O fluxes rather than soil sequestration. Lange (2011), considered transitions from both grassland and degraded grassland and for wheat found that emissions savings associated with LUC were both positive and negative depending on grassland type, with more productive grassland conversion found to have a smaller change in soil carbon. Hillier *et al.,* (2009) show that all emissions were increased following grassland conversion to either OSR or wheat.

There is likely to be a negative impact on GHG balance of transition from grassland to first generation bioenergy cropping systems.

Grasslands could also be considered as a source of energy themselves; for example Tilman *et al.* (2006) suggested that a low-input, high-diversity prairie systems involving mixtures of native grassland perennials can provide more usable energy, greater environmental benefits, and less agrichemical pollution per hectare than corn-ethanol or soybean biodiesel. However, in recent experimental work, this notion has been questioned, since the low biomass yields in such biodiverse systems (~4 tonnes ha^{-1} y^{-1}) do not compare favourably with those of switchgrass and *Miscanthus*.

Biodiverse grasslands are unlikely to provide significant yields enabling them to compete commercially with bred varieties of perennial bioenergy grasses and should not be considered further as sources of biomass feedstock.

3.3 Management Practices and their relevance to bioenergy

Management practices are important when assessing GHG and soil carbon impacts on the land regardless of the land-use type. The way the land is managed is one of the key contributors to the GHG balance and soil carbon, this can be done in such a way to reduce emissions, but more frequently is referred to in the literature as a means by which we are causing an excess of emissions, such as modern agriculture.

Several strategies are now being employed to encourage carbon sequestration and to minimise disturbance that may cause a large release of emissions into the atmosphere. These include, but are not limited to retention of residues on the soil, decreased/optimised fertilizer application, reduced or no-tillage and reduced/optimized irrigation. It should be remembered that current and past breeding for yield may have mitigated against soil stability and improved GHG balance. Future breeding and management are much more likely to be focussed on 'efficient crops' that are managed for optimum rather than maximum yields (Kell

Work undertaken by the IPCC investigated the potential GHG mitigation strategies available to us and how we can manipulate current agricultural practises to aid carbon mitigation. Table 8 shows the GHG savings that could be made if certain land management strategies were improved from their current state, including the use of bioenergy crops as a whole.

Mitigation Strategy	Mitigation potential (t CO_2-eq ha^{-1} y^{-1})	Climatic Zone
Improved crop management	0.39 – 0.98	Dry and moist
Improved nutrient management	0.33 – 0.62	Dry and moist
Improved tillage and residue management	0.17 – 0.35	Cool-dry & warm-dry
Improved tillage and residue management	0.53 – 0.72	Cool-moist & warm moist
Improved water management	1.14	All climatic zones
Bioenergy crops	0.17 – 0.35	Cool-dry & warm-dry
Bioenergy crops	0.53 – 0.72	Cool-moist & warm moist

Table 8 - IPCC mean estimate of GHG-mitigation potential of management strategies (From Smith *et al.,* 2007)

To enable the soil to be used as a sink for anthropogenic sources of excess CO_2 from the atmosphere, the amount of SOC needs to be increased. This can be done by increasing the amount of SOM which enters the soil and this can be achieved by changing the way crops are managed, Lal *et al.* (1999) suggested these need be as simple as conservation tillage, irrigation, reducing/eliminating fallow and retention of crop residues.

The above mentioned management strategies will be discussed in this report in the context of bioenergy crops, whilst other land-use and management strategies for increasing carbon sequestration exist, they will not be discussed due to lack of relevance to bioenergy cropping systems. The use of these management strategies will vary largely based on the crop being assessed and may not be relevant to all crop types.

3.3.1 Tillage

Current understanding of tillage impacts on soil carbon

Tillage is defined as the practice where soil is prepared for planting by mechanised disturbance using digging and overturning. Several types of tillage exist, namely conventional tillage, conservation or reduced tillage and no-tillage and these categories refer to the amount of soil disturbance and amount of residue that is buried. Once a crop has been harvested there will be residue left on the surface. Conventional tillage will cause almost all residues to be turned and mixed in with the soil, with less than 10-15% residue left on the soil surface. Reduced or conservation tillage will leave between 15-30% of residues on the soil surface and in a no-tillage system, the ground is not tilled but will only be disturbed during planting.

Within the literature there is general agreement that reduced tillage provides less disturbance and therefore will be a more suitable means of sequestering carbon within the soil compared with conventional tillage (Paustian *et al.,* 1997, van Groenigen *et al.,* 2011, Chen *et al.,* 2009). Decreased disturbance results in decreased aeration, decreased soil erosion, water and heat/thaw cycles, minimised oxidation of organic matter and encourages better aggregation, all contributing to the stabilization of soil organic matter (References within Lennon & Nater, 2006). The IPPC guidelines for GHG accounting inventories suggest a multiplication factor of 1.0 for a conversion from conventional tillage to reduced tillage (Houghton *et al.,* 1997), which translates to an approximate SOC increase of 10% (West & Post, 2002). Paustian *et al.* (1997) showed in a comparison of 39 paired sites (conventional tillage vs no-till) that soil carbon was 8% (285 g m^{-2}) higher when subjected to a no-till management regime. It should be noted that the compared studies were not necessarily looking at the GHG balance and soil sequestration potential of the two management regimes, so are likely an under-estimate of the effect of reduced tillage on carbon storage. In a global analysis of the effect of tillage on soil C sequestration, West & Post (2002) found that a switch from conventional tillage to no tillage can sequester 57 ± 14 g C m^{-2} yr^{-1} and that the majority of the SOC change seen occurs in the first 10-15 years following the switch over. Reduced tillage encourages SOM accumulation by reducing disturbance of the soil and limiting soil and residue contact (Carter, 1992). Reduced tillage shows an increase in bulk density in the upper soil layers (~0-30 cm) (Van Groenigen *et al.* 2011, Dolan *et al.,* 2006).

Whilst many have found reduced or no-till treatments to sequester more carbon than their conventional tillage counter parts (Van Groenigen et al. 2011, West & Post, 2002, Ogle *et al.,* 2005), there remain inconsistencies. It appears that the amount of sequestration may often be equivalent, but the distribution of stored carbon may differ along the entire soil profile (Dolan *et al.,* 2006; Blanco-Canqui & Lal, 2008; Angers *et al.,* 1997, Vanden Bygaart *et al.,* 2002). Dolan et al. (2006) and others showed that the amount of soil organic carbon and soil nitrogen was significantly higher in the no-till treatments compared to conventional tillage for the top 0-15 cm of soil. They found 15-20 cm to be a transition zone where there was no significant difference in SOC or soil N, but then for the deep parts of the profile, 20-45 cm conventional tillage showed a higher amount of SOC and soil N. When summating for the entire profile (0-45 cm), there was no significant difference in SOC between tillage treatments, but soil N was significantly higher in no-till treatment (Dolan *et al.,* 2006). This shows that while reduced tillage is often favoured for its environmental impacts, it may be less effective than thought as a management tool for soil carbon sequestration, with effectiveness determined by soil type, nitrogen treatments and other soil characteristics such as fungal community (Six *et al.,* 2004). In a review of our current knowledge on tillage and carbon sequestration, Baker *et al.* (2007) reported that the majority of studies have only sampled soil to a depth of 30 cm, this perhaps being the reason why there is widespread preference for reduced/no-till systems. However, studies which sampled to lower depths found no significant difference in carbon storage between conventional and reduced/no-till systems and in many cases found that more C was stored beneath conventional systems (Baker *et al.,* 2007, Blanco-Canqui & Lal, 2008). It should also be highlighted that many studies on tillage are taken on small experimental plots which minimise interference of other variables which is important for establish effects, but is not necessarily how these management strategies will be put into practice on a commercial scale (Blanco-Canqui & Lal, 2007)

Dolan *et al.* (2006) found that the profile effect documented for SOC and soil N was the same for bulk density (higher in conventional tillage surface soils but lower below 30 cm compared to no tillage) and for the δ13C signature (less negative in surface soils for conventional tillage and then more negative below 30 cm compared to no tillage). This also appears consistent with other findings (Blanco-Canqui & Lal, 2008), and it is recommended that future research on bioenergy LUCs should consider the whole soil profile in some detail. In a meta-analysis by Angers and Eriksen-Hamel (2007), it was concluded that effects of no-tillage on soil organic C content above and below 35 cm differed, and this was an extensive study using more than 25 pieces of original research, varying from 5 to 30 years duration. The authors were unable to identify why they found a significant stock change in SOC between no-till and till with increased SOC above 35 cm, with a relative accumulation of SOC at depth in the tillage regime. This was a general conclusion not limited by soil type. It is important to understand this transition in order to achieve effective soil carbon sequestration.

In addition to soil profile depth, several studies have highlighted the importance of sampling strategy to ensure a full picture of what is occurring is captured (Dolan *et al.,* 2006, Blanco-Canqui & Lal, 2008). This includes one of the largest and most highly cited reviews on the effects of tillage on C sequestration, which drew many of its conclusions from studies which only sample the top 30 cm of soil (West & Post, 2002). It is important to remember that the effect of tillage on SOC and soil N are site- and soil-specific, leading many studies to have highly variable results (Blanco-Canqui & Lal, 2008, Chen *et al.,* 2009, Lennon & Nater, 2006, Dolan *et al.,* 2006)

Tillage and bioenergy cropping systems

Bioenergy cropping systems encompass both annual and perennial crops, with the assumption that no-till operations associated with perennial crops are likely to lead to enhanced SOM and soil carbon. In general, in the context of bioenergy crops this type of land preparation would be expected to occur more often for first generation crops (annual crops such as wheat and sugar beet) than for second generation crops (lignocellulosic such as willow and *Miscanthus*). However, the long term effects of the tillage may be offset by the fact that 2G crops will be in the ground for at least a 10 year cycle. From the above literature, it can be concluded that there is still a lively debate occurring since the effect of a change from conventional tillage to reduced/no-tillage may merely redistribute the carbon in the soil profile than affect the amount of carbon stored.

The magnitude and direction of change in soil carbon in relation to no-tillage treatments in bioenergy cropping systems remains uncertain and future work should focus on long-term experiments where soil profiles to 1 m are sampled with replicated tillage and no-tillage plots under different land use regimes in side-by-side comparisons.

3.3.2 Residues

It seems the most appropriate topic to follow tillage is the effects of residue management on the soil C and GHG balance of the soil, due to the close link these two management practices hold. Residues may be defined in agricultural use as the parts of the crop which are not harvested and as a result are left on the soil. In bioenergy chains, residues have another meaning in that they can be the 'remains', 'wastes' or more commonly 'co-products' following primary energy or chemical extraction from the feedstock, and their end-use may have a large impact on the whole life cycle carbon cost of the bioenergy chain (Whitaker *et al.,* 2009).

Whether the residues are left on the soil or are removed will depend on the management regime of that crop, whether the residues can be used as biomass, and economic limitations of the plantation. Residues as co-products of some crops can themselves be used as a renewable source of energy by conversion to bioethanol, which holds some great potential according to several authors, for example for the US alone, 244 million Mg of stover could be used to produced bioethanol every year (Tally, 2000). Another option currently being considered for the use of crop residues is the CROPS idea: Crop Residue Oceanic Permanent Sequestration. This is where crop residues are transported deep into the ocean floor to help sequester carbon dioxide, a technique boasting to be the most permanent and rapid solution to removing CO_2 from the atmosphere (Stand & Benford, 2009). Whilst both of these ideas are interesting, one must consider the effect this removal will have on the land and the cost and benefits associated with these techniques. It appears from the literature that residue removal is generally considered detriment to the management of crops, but this is can vary depending on the soil and crop type (Andrews, 2006).

Residue retention can have various positive effects on the soil including decreased soil erosion and runoff, increased SOM, increased soil function, decreased disease-producing organisms, increased crop yields, enhanced soil biodiversity from habitat and substrate and increased soil sequestration (Andrews, 2006, Lal 2008, Franzleuebbers 2002). Many of these positive effects are interdependent and highly interactive with one another, and this has been summarised by Lal (2008) and can be seen in Figure 9. Much of the above discussed benefits are very direct effects on the soil but removal of residues also has indirect effects such as compaction from the increased use of machinery during removal which can in turn affect root growth and increase soil erosion (Wilhelm *et al.,* 2004). Here we will briefly discuss some of these benefits in more detail providing examples from experimental trials.

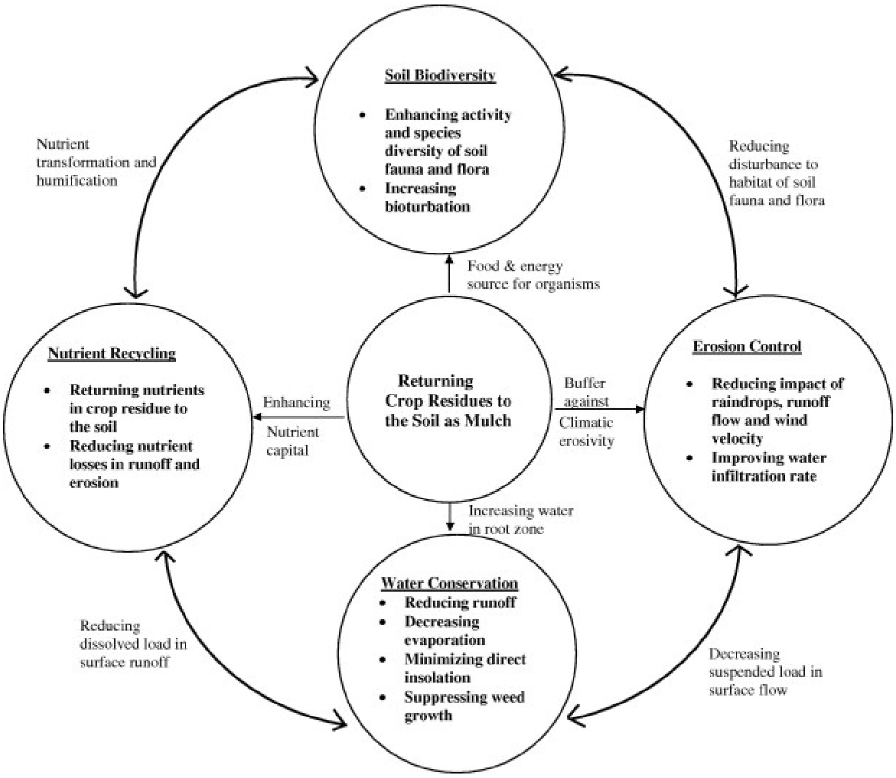


Figure 9 - The interacting benefits of returning residues to the surface. (Adapted from Lal, 2008).

The surface cover provided by crop residues is extremely important and it is this loss of cover which results in many of the detrimental effects we see when it is removed. For example, residues largely influence the radiation balance and energy fluxes of the soil thereby reducing the evaporation rate (Wilhelm *et al.,* 2004). This is also linked to the change in yield seen when crops are removed. The effect of residues on yield, like all other effects, varies depending on soil type, crop and climate. Some authors have found a positive effect (e.g., Wilhelm *et al.,* 1986; Linden *et al.,* 2000); Wilhelm *et al.* (1986) found reduced grain and biomass yield for corn and soybean crop attributable to reduced water availability and increase soil temperature. Whilst others have found negative effects, where, in certain conditions, yields can be decreased by 10-20% (Lal, 2008). Ismayilova (2007) showed that the removal of 2/3rds of forest residues results in increased surface run off, increased sediment yield and increased transport of nitrogen and phosphorus. But it did show a decrease in the level of nitrate in the ground water of that area.

Residue retention is considered a major management strategy for sequestering carbon into the soil sink; calculations have estimated that global retention of residues on croplands can sequester 1 billion Mg C/y which is equivalent to 30% of the annual increase in atmospheric CO_2 (Karlen *et al.,* 2009). There have been many examples in the literature to support this contention: Bushford & Stokes (2000) estimated a 60% increase in soil C storage when residual slash is incorporated into SRC poplar plantations; Dolan found that retained stover residue stored significantly more SOC and soil N across the whole of the soil profile (0-45 cm).

It is clear that the ability to increase soil sequestration from the retention of residues is due to the increased C inputs. This was nicely shown by Paustian *et al.* (1992) using the CENTURY model, where there was a positive linear relationship between C inputs and SOC change; these findings have been confirmed by many field observations (see Refs within Wilhelm *et al.,* 2004). In a recent review, Lemke *et al.* (2010) reviewed 35 studies, finding 27 of these reported increase soil C for residue retention but only 7 of which were significant.

Quantitative data to compare the removal of residues for energy purposes or the remainder in the soil for sustainability and GHG balance are limited, but are likely to be crop specific. In the UK context, with future emphasis on SRC and Miscanthus which have minimum residues, this is likely to not be an issue of significant concern.

In summary, it is extremely important for soil health that residues remain, due to the various benefits as described above; this also has the benefit of saving money for the land managers as work is not required to remove and dispose of residues. In a comparison of the use of residues for ethanol production versus improving soil quality, Lal (2008) concluded that residues should be retained to improve soil quality, despite the large potential for producing bioethanol from residues.

3.3.3 Fertilizer

Several reports in this review suggest that the largest component of GHG balance in bioenergy cropping systems is that determined by fertilizer usage and consequent N_2O

emission, with associated increased nitrates in soil and water, run-off leading to eutrophication and long-term application leading to decreased soil health. Over 30 million tonnes of fertilizer was utilized in the EU in 2008, with 7.1 million tonnes of this being nitrogen surplus – equivalent to 55 kg N ha^{-1} (Henriksen *et al.,* 2011). Fertilizer production also has a CO_2 cost, with the production of inorganic fertilizer using 1.2% of the world's energy and being responsible for 1.2% of global GHG emissions (Kongshaug, 1998).

The use of fertilizers is largely associated with first generation energy crops, in the UK context, but can also be applied to second generation energy crops such as SRC willow and *Miscanthus*, particularly when yields may begin to decline after third rotations; however, limited experimental evidence or commercial practice is available on which to make generalisations. The application strategy will vary dependant on the individual needs of the sites, but generally first generation bioenergy crops are fertilized every year. For SRC and *Miscanthus* which grow very rapidly, it is difficult to fertilize in the years after establishment, so all fertilization is usually completed in year one.

There are two broad categories of fertilizer, namely organic and inorganic. Organic fertilizers are a more traditional means of fertilizing crops and can include manure - the faeces of animals such as cows and horses - and sewage sludge which is produced from an array of organic and sewage wastes. Inorganic, or chemical fertilization, is the most widely applied type of fertilizer in UK agricultural practices; most commonly this is made up of phosphorus (P), potassium (K) and nitrogen (N) in varying ratios depending on the user needs. The rise in atmospheric nitrous oxide (N_2O) is the main consequence of fertilizer application and animal production (IPCC, 2007a), and is of particular concern as a GHG because it is 298 times more potent than CO_2 (IPCC, 2007b). An understanding of the point at which fertilizer application will no longer benefit yield and also limits the amount of nitrous oxide flux coming from the soil is important to maximise economic benefits and minimise environmental impacts. A small decrease in the amount of fertilizer can show large changes in the amount N_2O flux; for example, a study of a corn-wheat rotation showed that reducing fertiliser by only 25 kg N ha^{-1} (to 125kg N ha^{-1}) caused a 34% reduction in N_2O flux without significantly changing yield (Sehy *et al.,* 2003). One estimate of this equilibrium amount of N-application has been suggested for corn-soybean rotations in the Midwestern US at 135kg N ha-1 - a value which restricts N_2O emissions and does not significantly affect yield (Sawyer *et al.* 2006)

It is also important to understand the way in which these emissions arise and the time frames over which they occur after fertilizer application. In a comprehensive study by Hoben *et al.* (2011), it was shown that the increase in soil inorganic N occurred within 11 days of application and the majority of the N_2O emissions occur in weeks 4-8 after application. They concluded that the way in which these fluxes occur are non-linear, and often exponential with increasing N concentration after fertilizer application, with 180 and 225 kg N ha^{-1} causing a 44% and 115% increase in N_2O flux over the baseline 135 kg N ha^{-1}. Other studies have highlighted the long duration over which N_2O fluxes continue to be seen after application: for SRC willow and poplar, enhanced N_2O emissions were seen for up to 4 weeks (Hellebrand *et al.,* 2008).

As well as chemical fertilization, sewage sludge can be used as an agricultural fertilizer as it contains essential crop nutrients, such as nitrogen and phosphorus. The UK produces approximately 1.35 million tonnes annually, a proportion of which is used as an agricultural fertilizer (UK Water Report, 2009), so there is great potential to use this as an alternative to chemical fertilizers. Potential advantages of using sewage sludge is the fact that 40-60% of the nitrogen is inorganic (Defra, 2003), therefore readily available for the plant to use, and the main attribution of emission from N application is due to the organic fraction of the nitrogen occurring though processes of nitrification and denitrification in the soil. Gilbert *et al.* (2011) compared the effect of inorganic fertilizer and sewage sludge to a no fertilizer reference scenario LCA, and found that inorganic fertilizer increased the Global Warming Potential by 2% and sewage sludge increased it by a lower extent when applied to SRC willow and *Miscanthus*. This translates to a need for a <0.2 t/ha yield increase to offset the emissions associated with producing these fertilizers. Applications of sewage sludge and waste water as a means of fertilizing bioenergy crops has also proven to be economically advantageous in Europe due to increased yields and reduced fertilization costs (Dimitriou & Rosenquist, 2011; and references within)

Several studies have shown that addition of organic fertilizers can increase SOC (Iazurralde *et al.,* 2001; Kaur *et al.,* 2008, Fronning *et al.,* 2008, Hellebrand *et al.,* 2008). In a comparison between organic and inorganic fertilizers on SOC under a maize-wheat cropping system it was shown that in both cases SOC increased, and those active fractions of SOC increased significantly, specifically for the integrated use of both organic and inorganic fertilizer (Kaur *et al.,* 2008). In a perennial cropping system of SRC willow and poplar, fertilizer blocks showed increased SOC, perhaps due to increased crop residues, whereas non-fertilized blocks experience significant decreases in SOC (Hellebrand *et al.,* 2008). This study also showed that annual crops had higher N_2O fluxes than perennial SRC willow and poplar.

Different bioenergy crops are able to utilise different amounts of N-fertilizer; for example, in a comparison between annual and perennial crops it was shown that annual cropping combined with fertilizer application doubles the amount of N_2O emissions (4.3kg ha^{-1} vs. 1.9kg ha^{-1}), indicating that the use efficiency of nitrogen was greater for perennial plants (Kavdir *et al.,* 2008). Corn, a principle feedstock in the USA, has the highest application rates of both fertilizer and pesticides per hectare (FAO, 2008) whereas an SRC willow plantation will often be unfertilized and has very few pests.

Large scale cultivation of bioenergy crops requires that all species grown are consistent and reliable in terms of yield and response to management treatments such as fertilizer. Work conducted with SRC poplar, to be used as an energy crop, showed that while landfill leachate fertilization was able to increase aboveground biomass the trait response of these trees varied depending on the clonal variety treated (Zalesny Jr. *et al.,* 2009). Whilst it is important to plant mixed varieties to increase resistance of the crop as a whole, such clonal variation can be problematic in terms of economic returns for fertilizer applied versus yield out, which may be off putting to certain farmers. Therefore in order for the cultivation of bioenergy crops to remain an attractive investment such variation needs to be restrained to within reasonable limits. Very recent work on SRC and *Miscanthus* suggests that nitrogen fertilizer application may be the most significant management practice determining GHG balance (Drewer *et al.,* 2012).

Fertilizer application in bioenergy cropping systems may lead to large emission of N2O, contributing the most significant part of the GHG balance for these cropping systems. Future efforts to improve NUE (nitrogen use efficiency) are urgently required, as are management strategies to reduce unnecessary fertilizer use.

3.3.4 Water use and irrigation

The water footprint of bioenergy cropping systems has proved to be controversial in recent years. In the USA, recent reports suggest detrimental effects on water supply following large-scale cultivation of perennial energy grasses such as *Miscanthus* (VanLoocke *et al.,* 2010; Phong *et al.,* 2011), with water-use increased more than 50% compared with maize. The water-use footprint of 13 biofuel/energy crops was recently estimated by Gerbens-Leenes *et al.,* 2009) and showed that Jatropha (a second generation crop) used more water than all first generation crops studied, including five times the water used for ethanol maize . However, all of these reports rely on *modelled data* or *inventories:* these are blunt tools with which to determine future policy, since there is very little experimental evidence on which to base model assumptions. These models also assume uniform cultivation across landscapes, but plantations can be managed and sited to more effectively use limited water resources. Indeed, when spatial water use and variation in crop cover were incorporated into hydrodynamic models, VanLoocke *et al.,* (2010) were able to identify less sensitive areas for *Miscanthus* cultivation and reduce predicted hydrological impacts. Such areas should be targets for experimental verification, enabling the development of prescriptions for hydrologically and environmentally sustainable *Miscanthus* cultivation. Water use in SRC and *Miscanthus* has been quantified and work by Finch and Richte (2008), suggests lower transpiration rates when compared to grass, winter wheat and maize; however interception losses due to an extensive canopy may be higher in *Miscanthus* (Finch and Riche, 2010). Vanloocke *et al.,* 2010), also showed that water use in *Miscanthus* could out-pace supply in many areas of the mid-west USA, so there is cause for concern. For SRC, it has been suggested that water use on a seasonal basis is greater than grass or arable crops and more similar to tall forest (Finch *et al.,* 2004), although recent work on a ForestGrowth-SRC, a process-based model has shown that water use efficiency in poplar may be twice that of willow (Tallis *et al.,* 2012), suggesting that there may be room for improvement in SRC genotypes if this high Water Use Efficiency (WUE) trait can be captured in future breeding programmes. It also highlights the limitations of process-based models parameterised for single genotypes, or from data sets in the literature, again representing blunt tools from which to make generalisations.

There is adequate data to suggest cause for concern for crop water use in SRC and Miscanthus, since water use may be greater than other crop types and may outstrip ecosystem water supply. The impacts of water-use, and interaction with droughted environments for soil GHG balance remain to be elucidated.

Irrigation is the practice of applying water to crops to aid their growth; plants which are not subject to irrigation are often referred to as ‘rain-fed’. Irrigation is sometimes necessary to ensure adequate yields and encourage desirable traits but is associated with additional costs to the farmer as well as potential environmental problems. Negative impacts of irrigation include water pollution from run-off, increased soil erosion, salinisation and over-abstraction, though it does have some positive impacts on certain landscapes, such as increased biodiversity through the creation of new habitats (Baldock *et al.,* 2000). Approximately 70% of all freshwater withdrawn globally is used for agricultural purposes (Comprehensive Assessment of Water management in Agriculture, 2007), so a potential increase in agricultural production, including bioenergy crops, could put global freshwater supplies under pressure through competition. Europe is expected to see increased winter rainfall and reduced summer rainfall leading to increased drought (IPCC, 2007b). This may increase the need to irrigate in future climates.

Additionally, increased temperatures will result in higher evapotranspiration thereby increasing the need for irrigation, even if rainfall is not dramatically different in the future (IPCC, 2007b). Land-use and water quality have bidirectional effects on one another; with land management having direct effects on water quality, but also the water quality of the land often dictating its use (Bhardwaj *et al.,* 2010).

However, current levels of irrigation in European bioenergy cropping are by no means excessive compared to the total amount of irrigation applied (crops food and fibre), with bioenergy crops using only 2.3% of the total irrigation water consumed in Europe (Dworak *et al.,* 2009). Only 3.2% of the total cropping area in Europe is taken up by bioenergy crops and of this total area only 1.9% is subject to irrigation treatments (See Fig 10; Dworak *et al.,* 2009). In a study where three scenarios were examined ('business as usual', 'increased irrigation water demand' and 'water saving scenario') it was shown that even with future climates and a 4.5-fold larger bioenergy cropping area by 2020, that water availability will not present a problem for consumption by bioenergy crops (Dworak *et al.,* 2009). Even the scenario where water use is more restricted, it will not affect the ability to produce large amounts of biomass and in general the increased area will not require an increase in irrigation (Dworak *et al.,* 2009).

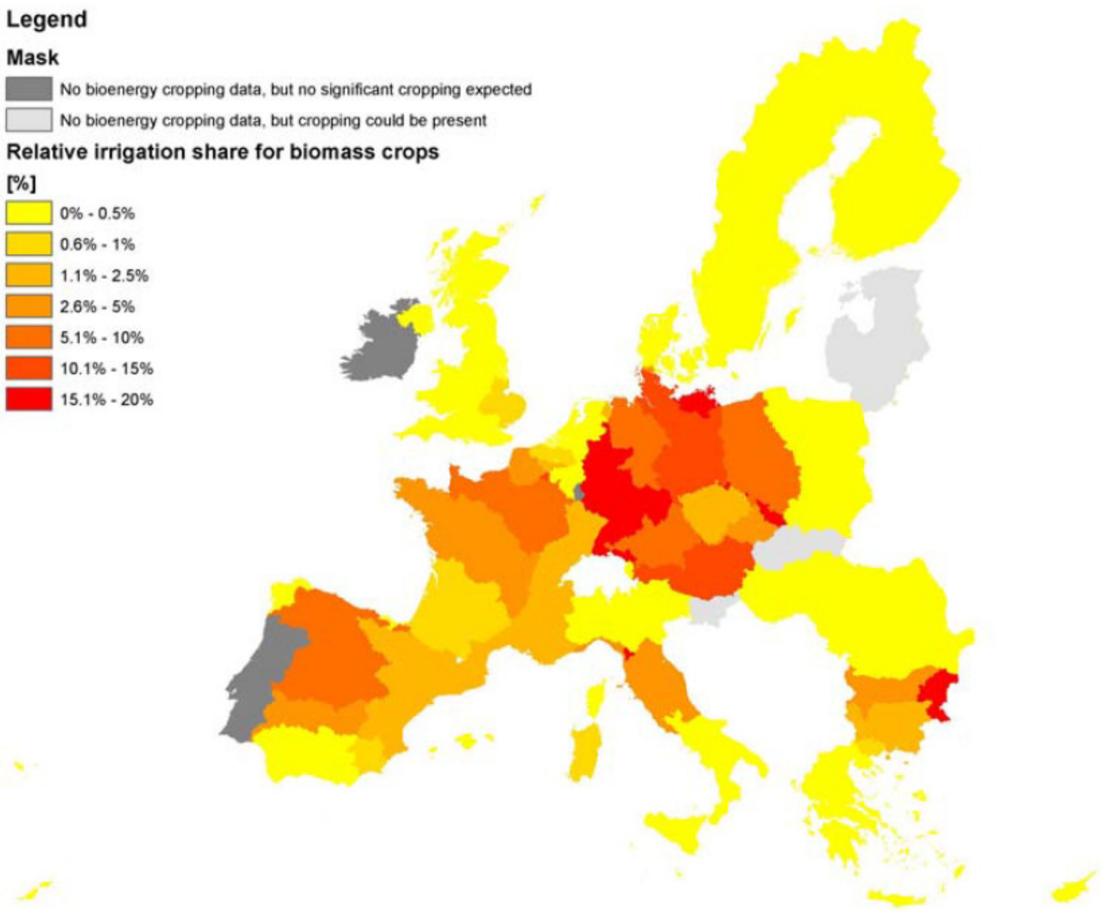


Figure 10 - Relative irrigation water consumption presented as a % of total irrigation water consumption for bioenergy crops (From Dworak *et al.,* 2009)

Presently, it is uncommon in the UK to irrigate plantations of second generation energy crops as the amount of rainfall is sufficient to support their growth to satisfactory yields, though irrigation is common in Mediterranean climates where summers are drier (Sevigne *et al.,* 2011). For example, ranges of applied irrigation for SRC poplar in different regions of Spain range from 2000-6500 m^3 ha^{-1} y^{-1} (Sevigne *et al.,* 2011, Sixto *et al.,* 2007), in some cases representing up to 48% of the total water consumption in high-density plantings (Sevigne *et al.,* 2011). Second generation *Miscanthus* generally has a much higher WUE (due to C4 photosynthetic pathway and a larger/deeper rooting system) and the amount of biomass used to contribute to the production of bioenergy crops is generally larger, with first generation grain crops only having about 50% of their aboveground biomass directly contributing to the production of biofuel (Wirsenius, 2000). First generation bioenergy crops therefore tend to continue to be treated as if they were cultivated for tradition purpose, be it food or fibre, by being subjected to a level of irrigation scheduling.

Proper applied use of irrigation as a management strategy to reduce GHG could be effected as an increase in biomass (as a result of irrigation) will lead to increased carbon sequestration as C is fixed into above and belowground biomass (Henriksen *et al.,* 2011). Partial root-zone irrigation is one of the latest methods which could be effective at reducing the environmental impacts of irrigation (Henriksen *et al.,* 2011). This method works by irrigating half the root zone and allowing the other half to dry out, with the side which is irrigated being alternated periodically to prevent permanent damage being done. It has been shown to have little effect on the yield and physiology of the plant compared to full irrigation and conventional deficit irrigation, and confers a significant increase in irrigation water use efficiency (IWUE) across many crop types (Sadras, 2009; Kirda *et al.,* 2007)

To conclude, irrigation has the potential to increase carbon sequestration due to increased plant biomass but remains an environmental threat from the perspective of water availability, particularly in the face of climate change. Though at present very few bioenergy crops are irrigated, the need for irrigation may increase with future predicted climates. More effective irrigation strategies have a role to play also in GHG savings through reduced use of automated farm machinery and better use of irrigation water.

4. FUTURE WORK

This review has confirmed the importance of the ELUM project in providing a set of timely and valuable data on transitions to bioenergy cropping for a range of crop types, and in different climatic zones of the UK. These datasets for net ecosystem C-fluxes and intensive quantification of GHG emissions, in addition to physico-chemical analysis of the soil, will be of global significance. In addition to this, the chronosequence study appears to be world-leading for bioenergy, given the number of sites and the sampling of soil down to 1 m in depth. This systematic search has provided a valuable database on which to test and validate models, although again, given the sparse datasets of value to the modelling activity, the site data from the ELUM network provide most valuable input for model testing.

The review has highlighted a number of trends and gaps:

- The site-based empirical data from both the network and chronosequence are providing valuable empirical data for model testing, both within and external to the project. For example, the project is not considering whole life cycle analysis (LCAs) and yet our data are of value in improving these tools for sustainability certification and assessment, particularly in a UK and European context. ***It is recommended that efforts are made to gain full impact of our research through better interaction with the LCA community and those developing sustainability toolkits for bioenergy in order to gain maximum impact from project results.***

- The site-based empirical data are of value, but the ELUM project will provide reliable data for only 2-3 years which in most instances fails to follow even one full harvest cycle (SRF and SRC) and even for *Miscanthus*, gives limited insight into long-term changes in soil carbon fluxes and stocks. ***It is recommended that the consortium maintain effort to extend and enhance the ELUM/CBC 'UK Bioenergy Network' including the addition of new work considering other ecosystem services, such as that in the recent NERC BESS application. This will gain maximum impacts from the sites for the benefit of UK policy makers and our scientific understanding of these crop transitions.***

- The review illustrates gaps in the literature. These are particularly apparent for forest transitions into first generation crops and uncertainties surrounding grassland transitions. For forests, the consortium should reconsider this transition, given the limited scope for enhanced planting of first generation crops for future feedstock supply and because in the UK context de-forestation goes against current policy and is unlikely to be an important LUC. In contrast - ***It is recommended that more detailed consideration be given to the grassland to bioenergy transitions, since it is here where there is the largest paucity of data and because this represents an important transition for the UK. GHG benefits of this transition remain uncertain and may depend strong on management regime, fertilizer use and grazing, as well as the age and soil conditions. Given these caveats, generalisations are difficult. ELUM goes someway towards addressing this with three contrasting grassland transitions underway, but a side-by-side comparison of different grassland managements and bioenergy transitions would be valuable in future.***

- Analysis of the literature reveals limited soils data that assess the whole soil profile down to 1m, and yet conflicting results on soil carbon sequestration are apparent, when only top soil layers are considered. ***It is recommended that ELUM continues with as much work as possible with soils to 1 m and that the grassland transition sites from both flux and chronosequence should be re-considered to ensure the maximum possible information will be available from them at the end of the project. A data matrix of these sites, with management and fertilizer inputs and C status of the soil should be constructed and considered for any additional action by the consortium.***

- The consensus for transition from annual arable to perennial grass and SRC crops suggests improved SOC, but the overall GHG balance to farm gate may be positive or negative and largely driven by fertilizer input and consequent N_2O emissions. Accumulation of SOC is in the range 0.44-1.1 Tonnes C ha^{-1} y^{-1}.

- There is likely to be a negative impact on GHG balance of transition from grassland to first generation bioenergy cropping systems.

- The magnitude and direction in soil carbon in relation to no-tillage treatments remains uncertain for bioenergy cropping systems but for second generation crops, with long rotation times, this may not be significant, although long-term experiment are warranted with soil profile sampling to 1 m.

- Quantitative data to compare the removal of residues for energy purposes or the remainder in the soil for sustainability and GHG balance are limited, but are likely to be crop specific. In the UK context, with future emphasis on SRC and *Miscanthus*, with minimum residues, this is likely to not be an issue of significant concern.

- Fertilizer application in bioenergy cropping systems may lead to large emissions of N_2O, contributing the most significant part of the GHG balance for these cropping systems. Future efforts to improve NUE (nitrogen use efficiency) are urgently required, as are management strategies to reduce unnecessary fertilizer use. There is a strong case for improved real-time instrumentation in the network of sites to capture this and other trace GHGs.

- There is adequate data to suggest cause for concern for crop water use in SRC and *Miscanthus*, since water use may be greater than other crop types and may outstrip ecosystem water supply. The impacts of water-use, and interaction with droughted environments for soil GHG balance remain to be elucidated.

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Appendix I: Full Methodology

A1.1 Search Methodology

The initial search method was developed in 2010 by Mathew J Tallis and was adapted by Zoe M Harris in 2011 when the work began. Searches were conducted using three commonly used search engines, namely Google Scholar, Science Direct and Web of Science. The use of different search engines was to ensure that all publications that fall under the criteria of our search were captured and the search was truly exhaustive. For example, Google Scholar is able to capture grey literature, such as governmental reports, which the other search engines will not capture. Science Direct was used as papers in its databases, provided by Elsevier, were excluded from results in Google Scholar searches at the time of the original searches, although this has now changed and may be one reason why between 2010 and 2011 the numbers of hits from Google Scholar showed an increase. Web of Science was searched using two techniques, one with speech marks around the search terms and the other without, as differences were found in the papers retrieved from the search from using either method. This is shown in figures and in text using: "WOS" or WOS, for each search technique respectively. The ability of Google Scholar to act as a scholarly search engine has been called into question since its beta release in 2004 (Jacsó, 2005). An understanding of search engine algorithms is important, enabling users to have an idea of how searches are performed, to assess the reliability of any search for their own purpose. Google does not disclose what algorithm they use but from several studies it appears that it uses a combination of ranking factors (Beel & Gipp, 2009a; Beel and Gipp, 2009b), taking different weightings compared to other search engines which allow the user to select how the papers are ranked; for example Science Direct allows users to select between relevance and date (Beel & Gipp, 2009a). It is apparent now, 7 years after its release, that Google Scholar is a contender in the scholarly domain and is challenging the more conventionally used search engines, Science Direct and Web of Science (Yang & Meho, 2006).

Search terms were defined and searched in a standardised format across the search engines with slight modifications made to suit the searching preferences of the particular engine. The search string was made up of four tiers, which allowed filtering of the papers through the searches and also allowed us to highlight the difference in area of interest between crop species (Fig 1). The results from these search engines were uploaded into a database for systematic review, but in the first instance the number of hits from the search was recorded. Search terms were defined to capture all literature which would contribute to covering the assessment of the effects of LUC to bioenergy crops in a UK context. SRF was initially one of the species terms used in the ETI contract but it was agreed at a later date, following our consultation with the consortium, that the individual species under SRF would provide a more effective search term, as these individual species terms captured references not captured by applying the generic term “SRF”.

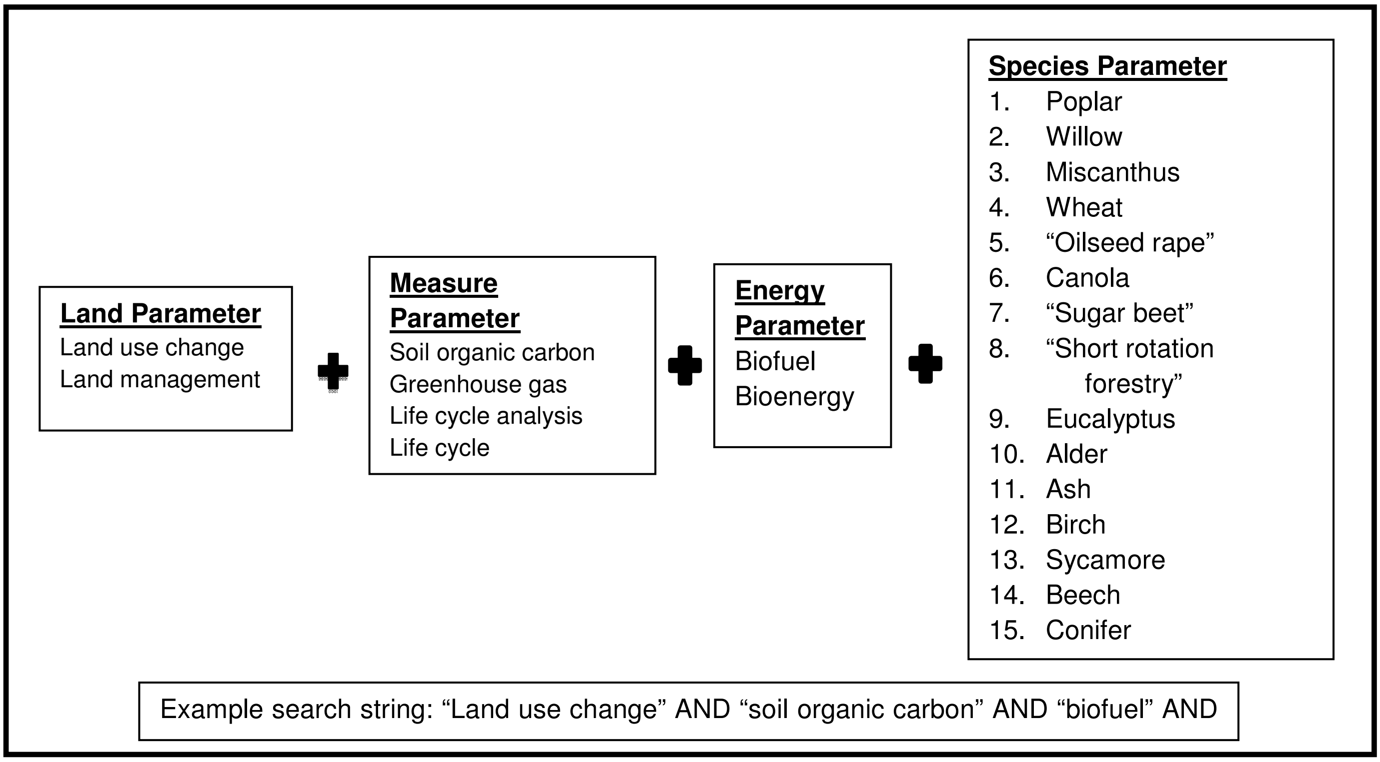

Figure 1 - Search terms used for systematic review and meta-analysis literature assimilation, following consultation with the consortium at month 2 of the project.

This search stage was comprised of 1024 unique searches which resulted in a total of 5786 individual references once duplicates were removed. These papers were firstly ‘raw processed’ by assignment of the categories ‘useful’ and ‘not useful’ based on a pre-defined selection criteria as outlined in the ETI contract. The criteria for section were:

- the location (to be UK applicable),

- the species concerned (inclusive of first and second generation bioenergy crops)

- the mention of the metrics which we used in the meta-analysis.

After this first round of processing, the papers were more carefully inspected to extract the data in pre-defined units for the meta-analysis, performing standard unit conversions if required. The metrics used for the extraction of data covered soil processes, GHG emissions and LCA are shown in Figure 2..

	Paramter		Unit
	Paper ID		
	Author		
	Year		
	Title		
	Transition from:		type or n/a
	Paper Type		Model/field/lab/database
	Measument year		
	Location		Latitude
			Longditude
	pH		
	Temp		°C
	Precipitation		mm yr^{-1}
	Yield		t ha^{-1} yr^{-1}
Different management Regimes	Fertilization		kg ha^{-1} yr^{-1}
	Tillage		Y/N
	Planting Density		plants ha^{-1}
	Crop Rotation		Crop & Length
	Irrigation		Y/N or n/a
	Residue		Y/N or n/a
Soil Texture	Class		
	Sand		%
	Silt		%
	Clay		%
	Bulk Density		g cm^{-3}

	Paramter	Unit
	Yrs after transition	Yrs
	Soil Organic Carbon	kg C ha^{-1} yr^{-1}
	Depth for SOC	cm
	Total Soil Carbon	Kg C ha^{-1} yr^{-1}
	Correction for bulk density	Y/N
GHG Net Emissions for crop life cycle	CO_2	Kg CO_2 eq ha^{-1} yr^{-1}
	N_2O	
	CH_4	
GHG for whole LCA	CO_2	Kg CO_2 eq ha^{-1} yr^{-1}
	N_2O	
	CH_4	
	Whole LCA for energy	(MJ_{in} :MJ_{out})
	Carbon Isotopic Soil Signature	‰
	Carbon Sequestration	kg C ha^{-1} yr^{-1}
	Dissolved Organic Carbon	µg C g^{-1} soil
	Below Ground Biomass	Kg ha^{-1} yr^{-1}
	Above Ground Biomass	Kg ha^{-1} yr^{-2}
	Litter Dry Matter	g yr^{-1}
	Litter Decomp Rate	k
	Root Decomp Rate	k
	Fine Root turnover	yr^{-1} or % yr^{-1}
	Conversions Made	
	Other Measurements	

Figure 2 - Data extraction parameters for meta-analysis including standard units for measurements

The data extraction parameters, as seen in figure 2, were chosen with WP4 in mind as they will contribute to WP4's limited simulation input data for running the model. This is important as it will allow more accurate outputs to be generated for a wider range of bioenergy scenarios that may have been previously missed bv modellers. Preliminary data sets were sent to Dr Marta Dondini at the University of Aberdeen to ensure all parameters were useful for model inputs before data extraction commenced. All the data from the papers in this deliverable will be passed onto Aberdeen to allow them periodically to enhance the model outputs.

A1.2 Meta-analysis

A meta-analysis is a method used in many types of science from the biological to the social. The purpose of a meta-analysis is to review previously published data in a rigorous way to provide a quantitative result, based on a proper statistical analysis. It allows the data from many papers to be amalgamated to help us identify trends, patterns and identify variation between studies – this is particularly important in many areas in science due to large volumes of data that are published rapidly (Rosenthal & Dimatteo, 2001). The most notable of meta-analyses conducted in the field of plant and environmental science is that of Curtis and Wang (1998) who looked at the response of woody plants to elevated $CO_{2.}$ Their work illustrates that the meta-analytical technique is well developed and suited to differential treatments. The main limitation of a meta-analysis in this context is the need for an 'effect size' metric which essentially is a control which all the bioenergy crop 'treatments' will be measured against to allow us to quantify their effects. In order to overcome that here, when control treatments are not available for the bioenergy cropping transitions, average data for that geographical region will be found from the literature and databases and applied accordingly. This should be acceptable but is time-consuming. A second major problem with the current meta-analysis on bioenergy crop transitions is availability of datasets. It is interesting to note that most of the ecological meta-analyses conducted to date (Medlyn *et al.,* 2001; Morgan *et al.,* 2003; Jeffery *et al.,* 2011) have been focused in areas where large amounts of funding with significant experimentation has been undertaken, globally, in many simultaneous studies. This has not been the case until very recently in the area of bioenergy cropping and soils, although new experimental studies, initiated from 2008 onwards are now becoming available for analysis. It was highlighted in a recent publication that the number of meta-analyses being conducted in the field of ecology has increased vastly in the past few years and in general, they are becoming an ever more powerful tool for elucidating the effects of multiple studies (Cadotte *et al.,* 2012).

Several software packages are currently available which allows one to conduct a full meta-analysis and there have been several studies examining their reliability and usability. If we look at classic reviews in life sciences such as Curtis and Wang (1998) and Gou and Gifford (2002), both of these used MetaWin to conduct their meta-analyses. However, Bax *et al.* (2007) provide a detailed and comprehensive review of six of the many available software packages available at present and found that MIX or CMA provide the best features and usability. Table 1 illustrates the analytical features available in each of the software packages however it must be kept in mind that software is very regularly updated and this may not be completely representative of current abilities of each software package.

Upon further investigation into these software packages it was discovered that MetaWin, which was first released in 1997, is now being self-distributed by the creators and the latest update was in 2007. The webpage for MetaWin also itself has not been updated since April 2011, suggesting limited maintenance which may lead to limited technical support should problems arise. There is evidence to suggest that many publications in the field of life sciences are still using MetaWin (Ainsworth & long, 2005; Wang *et al.,* 2012), however.

Other options that were considered in light of Bax *et al.* (2007) were CMA and MIX, upon closer inspection both seemed more up-to-date and better supported than MetaWin. Both programs have improved significantly since they were reported in Bax *et al.* (2007); for example MIX is no longer limited to 100 studies and now offers a professional version with a fuller suite of features. Given this, we have chosen MIX as the software for this study as it appears to be as effective as CMA and is also offered at a significantly cheaper price ($75 vs ~$395 for single student user).

	CMA	WEasyMA	MetaWin	MetAnalysis	RevMan	MIX
Computational setting options						
Number of decimals	✓	✓	✓			✓
Alpha level/confidence intervals	✓	✓	✓		✓	✓
Constant continuity correction	✓	✓	✓	✓	✓	✓
Treatment arm continuity correction						✓
Variance for mean differences	✓					✓
Variances for standardized mean differences	✓					✓
Bootstrap confidence intervals			✓			
Numerical output						
Individual study data	AM,CI,P,W,other	AM,CI,W,other	AM,other	AM,CI,other	AM,CI,P,W,other	AM,CI,P,W,other
Association measures – risk	RD,RR,OR	RD,RR,OR	RD,RR,OR	RD,OR	RD,RR,OR	RD,RR,OR
Association measures – means & standardized measures	MD,HG,CD,other		HG,other		MD,HG	MD,HG,CD
Association measures – other	CC,Z					CC
Fixed effect models/weighting	IV,MH,PETO	IV,MH,PETO,other	IV,MH,PETO	IV,MH,PETO	IV,MH,PETO	IV,MH,PETO
Random effects models/weighting	DL	DL	DL	DL	DL	DL
Cumulative analyses	Several variables	Several variables	Several variables	(✓) Only graph		Several variables
Heterogeneity	Q,I^2,τ^2	Q	Q	Q,I^2	Q,I^2	Q,I^2,τ^2,other
Small study effect/publication bias	FSN,RC,EGG,TF	EGG	FSN,RC	FSN,EGG		FSN,RC,EGG,MAC,TF
Meta-regression	Single moderator	✗	Single moderator			
Graphical output						
Forest plot	✓	✓	✓	✓	✓	✓
- Points proportional to weights	✓				✓	✓
- Annotations in rows possible	✓			✓	✓	✓
- Cumulative possible	✓			✓		✓
Funnel plot (I/se, se, var, N, P)	I/se,se	I/se,se,N	var,N	N	I/se	I/se,se,N,P
Galbraith plot		✓	✓	✓ (radial)		✓
Exclusion sensitivity plot	✓					✓
Trim and fill plot	✓					✓
L'Abbe plot		✓		✓		✓
Other plots			HIST,NQ			BOX,HIST,NQ,other
Graph formatting	✓	✓	✓	✓	✓	✓

The '✓' indicates the presence and no mark indicates the absence of a feature. The '(✓)' means that the feature is limited or partially in development, and the '✗' means it was not working correctly at the time of our assessments. Abbreviations: AM = association measure, CI = confidence interval, P = P value, W = weight, RD = risk difference, RR = risk ratio, OR = odds ratio, md = mean difference, hg = Hedges' g, cd = Cohen's d, CC = correlation coefficient, Z = Fisher's Z, IV = inverse variance weighting, MH = Mantel-Haenszel weighting, PETO = Peto's weighting, DL = Dersimonian & Laird weighting, Q = Cochran's or Breslow & Day's Q, I^2=Higgins's inconsistency statistic, τ^2=between study variance indicator, FSN = fail-safe number test, RC = rand correlation test, Egg = Egger's regression test, Mac = Macaskill's regression test, TF = trim and fill method, se = standard error, var = variance, N = sample size, TFP = trim and fill plot, HIST = histogram, NQ = normal quantile plot, BOX = box-and-whiskers plot.

Table 1 - Comparison of analytical features in available meta-analysis software packages (from Bax *et al.*, 2007)