Programme Area: Bioenergy

Project: ELUM

Title: Review of the Effects of Bioenergy Crops on Ecosystem Service in the UK Context

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 a review of the current research on key ecosystem services relating to bioenergy cropping systems in a UK context. It identifies current research gaps in this area and describes in detail the underlying provisioning services. Whilst much of the ELUM project focuses on an analytical understanding of the impacts of land-use change to bioenergy crops, this report focuses on what are sometimes less easily measured effects – impacts on all the goods and services that humans rely on, defined by the Millennium Ecosystem Assessment (MEA) as "ecosystem services". Although the concluding outputs from this Work Package 1 (WP1) report do not feed directly into other ELUM Work Packages, it nevertheless represents an important supporting body of evidence in the discussion around the potential uptake of bioenergy crops in the UK.

Context:

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

Some information and/or data points will have been superseded by later peer review, please refer to updated papers published via www.elum.ac.uk

ETI Project code: BI1001

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

Management & Deliverable Reference: PM06.1.4

Review of the Effects of Bioenergy Crops on Ecosystem Service in the UK Context

REPORT

V2.0

28th April 2013

Robert Holland, Donna Clarke and Gail Taylor

Faculty of Natural & Environmental Sciences, University of Southampton, Southampton, SO17 1BJ

DOCUMENT ID: BI1001_ELUM_PM06.1.4_ECOSYSTEM SERVICES V2.0.DOCX

EXECUTIVE SUMMARY

This report provides a detailed review of the current research on key ecosystem services relating to bioenergy cropping systems in a UK context; it identifies current research gaps in this area and describes in detail the underlying provisioning services.

Whilst much of the ELUM project focuses on an analytical understanding of the impacts of land-use change to bioenergy crops, this report focuses on what are sometimes less easily measured effects – impacts on all the goods and services that humans rely on, defined by the Millennium Ecosystem Assessment (MEA) as “ecosystem services”. Although the concluding outputs from this Work Package 1 (WP1) report do not feed directly into other ELUM Work Packages, it nevertheless represents an important supporting body of evidence in the discussion around the potential uptake of bioenergy crops in the UK. A number of key messages are highlighted, including where gaps in understanding could usefully be filled in this context (although not as part of this project).

The deliverable and acceptance criteria for this report are as follows:

Deliverable D1.4:	One report, that details current data/activities; identifies research gaps; identifies key ecosystem services; and detailed description of provisioning services
Acceptance Criteria:	The report must provide a detailed review of current and previous activities on iLUC (UK and international) and describe in broad terms the magnitude of potential iLUC displacements. Specifically, it must identify and assess other ecosystem services, including water mass balance, hydrology, bio-diversity, etc that are relevant to a sustainability assessment and opportunity mapping for the Bioenergy Crops identified above. Ecosystem services can be classified under the headings: provisioning (e.g. crop production,) supporting (e.g. soil fertility), regulating (e.g. climate change, groundwater protection) and cultural (e.g. aesthetics and recreation). This report will provide a high level description of all types of iLUC, including a sustainability matrix, but with detailed discussion on provisioning services only.

This report provides an up-to-date review on the relevant literature, which has allowed us to discuss current knowledge of the potential impacts on ecosystem service delivery, of the transition from arable, semi-improved grassland and forestry to those 2nd generation bioenergy crops, which are suitable for the UK temperate climate, namely short rotation coppice (SRC) Willow and Poplar, short rotation forestry (SRF) and the energy grass *Miscanthus*.

We have discussed ecosystem services under the headings “provisioning”, “regulating”, “supporting”, and “cultural,” as well as discussing the impact of bioenergy crops on biodiversity. In addition we have reviewed the current approaches to quantifying the indirect effects of land-use change, iLUC. A number of key messages, research gaps and priorities for future research have been highlighted from the literature:

- Across ecosystem services, evidence for the impacts of bioenergy production, and specifically transitions to 2nd generation crops, is sparse. Most information is available for transitions from 1st generation crops, with little information on transitions from marginal lands, grassland or forest habitats to 2nd generation crops.

- Most published research details impacts on, climate regulation, soil quality, water availability and water quality together with biodiversity. Across the four broad categories of service the majority of work is focused on regulating services.

- Compared to 1st generation crops, 2nd generation bioenergy crops would be expected to deliver benefits both in terms of protecting ecosystem services and delivering services in their own right. These benefits are a function both of the crop characteristics and differences in management practices.

- To understand impact of transition from 1st to 2nd generation crops it is necessary to examine the context in which the crop will be produced. Dependent on local conditions, the same crop has the potential to have positive or negative effects on ecosystem services.

- Compared to 1st generation crops the “low input” management associated with 2nd generation crops delivers many of the key benefits. However, as there is currently little large-scale production of 2nd generation crops it is possible that problems will emerge. There is evidence of trade-offs in terms of application rates of fertiliser and biomass production, and to be economically viable production may need to be of high intensity around bio-refineries. Such issues may reduce benefits to ecosystem services.

- For transitions from semi-improved grassland there was little evidence within the literature of impacts on ecosystem services. Based on studies examining marginal, abandoned or degraded land we were able to draw a number of tentative conclusions. Transitions to 2nd generation crops can have negative impacts on biodiversity (which underpins many services) and food production as expansion displaces livestock. However, such negative impacts are counterbalanced by improvements in other services, often mediated through soil quality improvement attributable to the crop characteristics and management practices of 2nd generation crops.

- Transitions from forest to 2nd generation crops are likely to be rare in the UK, and given the current policy background, this particular transition is unlikely to be relevant across the EU. Globally, land-use change associated with this transition is having a profound influence on the provision of ecosystem services.

- The impacts of indirect land-use change (iLUC) are complex and difficult to quantify. They cannot easily be measured but must be predicted from combining several modelling approaches including global economic models, biophysical and technical models. Despite this, it is clear that iLUC can add to the whole-cycle GHG balance of a bioenergy chain and may also have an impact on other ecosystem services. There are few published studies that consider 2nd generation grass and tree crops, rather the emphasis has been on 1st generation food crops.

- These studies reveal the iLUC impact of biodiesel chains is greater than that for bioethanol chains, but model assumptions determine the magnitude of this effect.

- The 2012 EC Directive supersedes much of the published information on iLUC since Europe now has a sustainability policy framework that includes iLUC. However, there are still significant gaps in our understanding of iLUC with many competing models with different strengths and weaknesses. There is a clear need to consolidate these approaches and to incorporate more data on 2nd generation crops.

- Currently there is considerable interest in both ecosystem services across the UK and the potential for bioenergy production. There is an opportunity to bring together these communities of researchers to close many of the research gaps identified in this report. Projects examining this issue should be multidisciplinary in nature incorporating both the natural and social sciences.

1. INTRODUCTION AND AIMS

Growing use of bioenergy and questions of sustainability

Meeting the world's growing energy demands while reducing the environmental impacts associated with energy production and use (Naik *et al.*, 2010), is a key societal challenge for the next fifty years (Foresight, 2011). It is within the context of environmental sustainability, alongside energy security, that the recent upsurge in production of bioenergy – particularly biofuel for transport - has emerged. Although biofuels have been used in transport since the early 20th century, the last few decades has seen a dramatic increase in production (Nigam & Singh, 2011) from 314,567 Barrels Per Day (BPD) in 2000 to 1,897,202 BPD in 2011 (U.S. Energy Information Administration, 2013). This rise has been driven by an increase in oil price over the same time period, making biofuel economically competitive, by policy commitments to increase energy security, and as a mechanism to reduce greenhouse gas (GHG) emissions (Balat, 2007, Bessou *et al.*, 2011, Sharman & Holmes, 2010).

Concurrent with increased production of bioenergy has been the emergence of a number of significant societal and environmental issues (Gasparatos *et al.*, 2011, van der Horst & Vermeylen, 2011). Firstly, what was crystallised in the "food vs. fuel" debate where additional demand for food-crops to produce biofuel was identified as one of a number of factors, including crop failure and market speculation that resulted in increased food prices and threatened food security (Ajanovic, 2011, Naylor *et al.*, 2007). Secondly, research has questioned whether the potential reductions in life-cycle carbon emissions of bioenergy are being realised. Factors such as land-use change may result in the release of as much, or potentially more, carbon during the life-cycle of a bioenergy crop as is produced by conventional fuels (Fargione *et al.*, 2008, Searchinger *et al.*, 2008, Smith & Searchinger, 2012) leading to significant "pay-back" times before carbon savings are realised (Searchinger *et al.*, 2008). Although these two issues are still hotly debated, it seems reasonable to conclude that both 'good' and 'bad' liquid bioenergy chains are possible and key policy decisions are required to ensure that future developments focus on the former. Bioenergy is diverse and flexible, covering many feedstocks, conversion processes and output pathways and could be an important alternative to fossil-fuel based energy when produced in a sustainable way. It has been suggested that 2nd generation bioenergy feedstocks grown specifically for the production of energy, are more environmentally friendly than 1st generation (food-crop) based feedstocks (Naik *et al.*, 2010, Rowe *et al.*, 2009) and so represent one pathway to sustainable production.

In October 2012 the European Union (EU) signalled a significant change in the Renewable Energy Directive (RED) by proposing to reduce the limit for the use of 1st generation based bioenergy from 10% to 5% (European Commission, 2012). As part of the proposal the EU will amend the RED and Fuel Quality Directives, increasing the required minimum GHG savings thresholds from 35% to 60%, and incorporate an indirect land-use change (ILUC) factor to account for carbon emissions from 1st generation feedstocks that arise as a result of displaced agricultural production, driving land-use change and associated GHG emissions (Arima *et al.*, 2011, Plevin *et al.*, 2010, Searchinger *et al.*, 2008).

The importance of ecosystem services

In 2005, the MEA recognised the global importance of the services that ecosystems provide, the reliance humans have on these, and the need to reverse their degradation. These ecosystem services were separated into four categories based on the type of service provided;

- ***Supporting*** services, that underpin and support the functioning of all other services, such as nutrient cycling, soil formation and primary production;
- ***Provisioning*** services such as food, fuel and freshwater;
- ***Regulating*** services such as pollination, climate regulation, disease and pest regulation and water purification; and
- ***Cultural*** services such as spiritual, aesthetic and recreational.

Within the UK, the UK National Ecosystem Assessment (UK National Ecosystem Assessment, 2011) provided an overview of the state of the UK natural environment, highlighting the importance of ecosystem services in a UK context.

As the concept of ecosystem services explicitly considers natural processes and the benefits that humans derive from them it provides a useful framework to examine the environmental and societal issues surrounding bioenergy (Gasparatos *et al.*, 2011). Despite recognition of the need to expand the consideration of the environmental and social consequences of energy production (McBride *et al.*, 2011), there has been no systematic analysis of the impacts of 2nd generation feedstocks on ecosystem services. Given policy drivers aimed to stimulate production of 2nd generation bioenergy, it is particularly pertinent to ask how transitions to 2nd generation feedstocks will influence the provision of services, and whether such transitions may provide ancillary benefits beyond reductions in GHG emissions.

This review provides details on the current data / activities relating to the impact of land-use change to bioenergy crops on ecosystem services, identifying impacts on key ecosystem services and research gaps. We focus on land-use change from arable, grassland and forestry to those 2nd generation bioenergy crop systems, which are suitable for the UK temperate climate, namely short rotation coppice (SRC) Willow and Poplar, short rotation forestry (SRF) and the energy grass *Miscanthus*. Where relevant, other crops currently not defined in the terms of reference, such as switchgrass, will be considered if the research provides relevant knowledge that can inform our understanding of the science. Crops, which are only suitable to be grown in tropical climates are outside the scope of this review and were not considered. Finally, we do not consider impacts related to soil carbon and wider greenhouse gases as these have been dealt with in detail as part of the meta-analysis and review completed in D1.3 and D1.5 as well as being a key output from the measurement and modelling activities in ELUM. The executive summary makes specific recommendations relating to research gaps and priorities for further research.

The acceptance criteria for D1.4 state: "The report must provide a detailed review of current and previous activities on iLUC (UK and international) and describe in broad terms the magnitude of potential iLUC displacements. Specifically it must identify and assess other ecosystem services, including water mass balance, hydrology, bio-diversity, etc that are relevant to a sustainability assessment and opportunity mapping for the Bioenergy Crops identified above. Ecosystem services can be classified under the headings: provisioning (e.g. crop production,) supporting (e.g. soil fertility), regulating (e.g. climate change, groundwater protection) and cultural (e.g. aesthetics and recreation). This report will provide a high level description of all types of iLUC, including a sustainability matrix, but with detailed discussion on provisioning services only".

We divide this report into two sections. The main body of the text (below) focuses on a number of key provisioning and regulating services and highlights major findings and points of interest. In the appendix to this report we provide a more detailed discussion of each of the ecosystem services considered and include discussion of a range of other services. Throughout the report we cross-reference to the relevant sections in the appendices.

What is the UK National Ecosystem Assessment?

The UK NEA could be thought of as a country specific version of the Millennium Ecosystem Assessment. The UK NEA was carried out between 2009 and 2011 and represents the first analysis to examine the UK's natural environment in terms of the benefits that it provides to human society and well-being. Using techniques across the natural and social sciences, the UK NEA examined the importance of ecosystem services across four broad categories; provisioning, regulating, supporting and cultural (see Table 1) reporting current status, trends in provision and drivers of change.

2. QUANTITATIVE REVIEW OF ECOSYSTEM SERVICE AND BIOENERGY STUDIES

Our review is based on a search of ISI Web of Science using the term ‘biofuel’, ‘biodiesel’, ‘bioethanol’, or ‘bioenergy’ together with keywords relating to commonly examined ecosystem services (Millennium Ecosystem Assessment, 2005, UK National Ecosystem Assessment, 2011). We identified studies that examined land-use transitions based on three reference states, 1st generation crops, marginal land and natural habitat (subdivided as grassland or forest). Studies were included that either measured a direct transition through time from the reference to 2nd generation bioenergy production, or used a space for time substitution contrasting provision of service/s under a reference state against provision under 2nd generation production (see appendix A1 for detailed method).

With 124 effects identified, Table 2 (for energy grasses) and Table 3 (for woody crops) illustrate that comparatively few studies have used a reference approach to understand impacts of 2nd generation production on ecosystem services. Published research is not evenly distributed across crops and transitions. Across all reference states the majority of research has examined impacts on regulating services (specifically climate regulation), and most comparisons have been made with 1st generation feedstocks. Only 11 effects were found for transitions from marginal land to 2nd generation feedstocks, and only 26 for transitions from natural habitat. We now examine in detail how 2nd generation crops can influence a number of key provisioning and regulating services.

Table 1: Services examined and keywords used as search terms in ISI Web of Science review.

Service	Keywords	Total
Crops and livestock	Livestock; food; fibre; Pasture; Forage	481
Fisheries	Fisheries; fish	108
Aquaculture	Aquaculture; fish	130
Timber and forest products	Timber; Forest; Forestry; fungi	578
Honey production	Bees; Honey	10
Genetic resources	Genetic diversity; biodiversity	158
Water quality and quantity	Water quantity; Water availability: Water quality	101
Ornamental Resources	Flowers; horticulture	20
Climate regulation	Carbon; Greenhouse gas; Nitrogen; evapotranspiration; albedo	2031
Hazard regulation	Erosion; Flooding	98
Disease and Pest Regulation	Pests; Disease	115
Pollination	Pollination; Pollinators; Bees	17
Soil quality regulation	Soil; soil cycling; Nutrient cycling; carbon	1934
Noise regulation	Noise	0
Air quality regulation	Particles; Ozone; Ammonia; Nitrogen; Sulphur; Air quality	903
Water quality regulation	Eutrophication; Water quality	339
Soil formation	Soil formation; Dissolved organic carbon; DOC; weathering	123
Nutrient cycling	Nitrogen cycle: nitrogen; mineralisation; phosphorous	799
Water cycle	river; water cycle; lake; Groundwater	305
Primary productivity	Primary productivity	16
Religious and Spiritual	national parks; protected areas; spiritual	16
Heritage Goods	Community; cultural; heritage	214
Landscape	Landscape; national parks; protected areas	170
Human Health	Human health; health	44
Leisure and Tourism	Leisure; tourism; national parks; protected areas; recreation	119

Table 2: Impact of herbaceous sources of bioenergy on the provision of ecosystem services compared to different reference conditions. (Blank cells indicate no returned studies).

Ecosystem Service	**Replace 1st Gen.**			**Replace marginal**			**Replace grassland**			**Replace forest**		
	+ve	-ve	Neu.	+ve	-ve	Neu.	+ve	-ve	Neu.	+ve	-ve	Neu
Crops and livestock	1	2			2	1						1
Fisheries												
Aquaculture												
Timber and forest products					1							1
Honey production												
Water availability		4										
Ornamental Resources												
Climate regulation	14	7		1	2		1	1		1	4	1
Hazard regulation	6			1				1				
Disease and Pest Regulation	3											
Pollination	2											
Soil quality regulation	3		2	2			2	1	2			
Noise regulation												
Air quality regulation	4	1	2				1					
Water quality regulation	9	2			1						1	
Soil formation								1				
Nutrient cycling	3		2									
Water cycle		3										
Primary productivity							2	1				
Protected areas												
Spiritual												
Cultural												1
Landscape												
Human Health	5											

Table 3: Impact of lignocellulosic sources of bioenergy on the provision of ecosystem services compared to different reference conditions. (Blank cells indicate to returned studies).

Ecosystem Service	**Replace 1st Gen.**			**Replace marginal**			**Replace grassland**			**Replace forest**		
	+ve	-ve	Neu.	+ve	-ve	Neu.	+ve	-ve	Neu.	+ve	-ve	Neu
Crops and livestock												
Fisheries												
Aquaculture												
Timber and forest products												
Honey production												
Water availability												
Ornamental Resources												
Climate regulation	11							1				
Hazard regulation												
Disease and Pest Regulation												
Pollination												
Soil quality regulation								1				
Noise regulation												
Air quality regulation												
Water quality regulation										1		
Soil formation												
Nutrient cycling												
Water cycle												
Primary productivity												
Protected areas												
Spiritual												
Cultural												
Landscape												
Human Health												

3. SYNTHESIS CASE STUDY - IMPACTS OF BIOENERGY ON ECOSYSTEMS IN THE UK

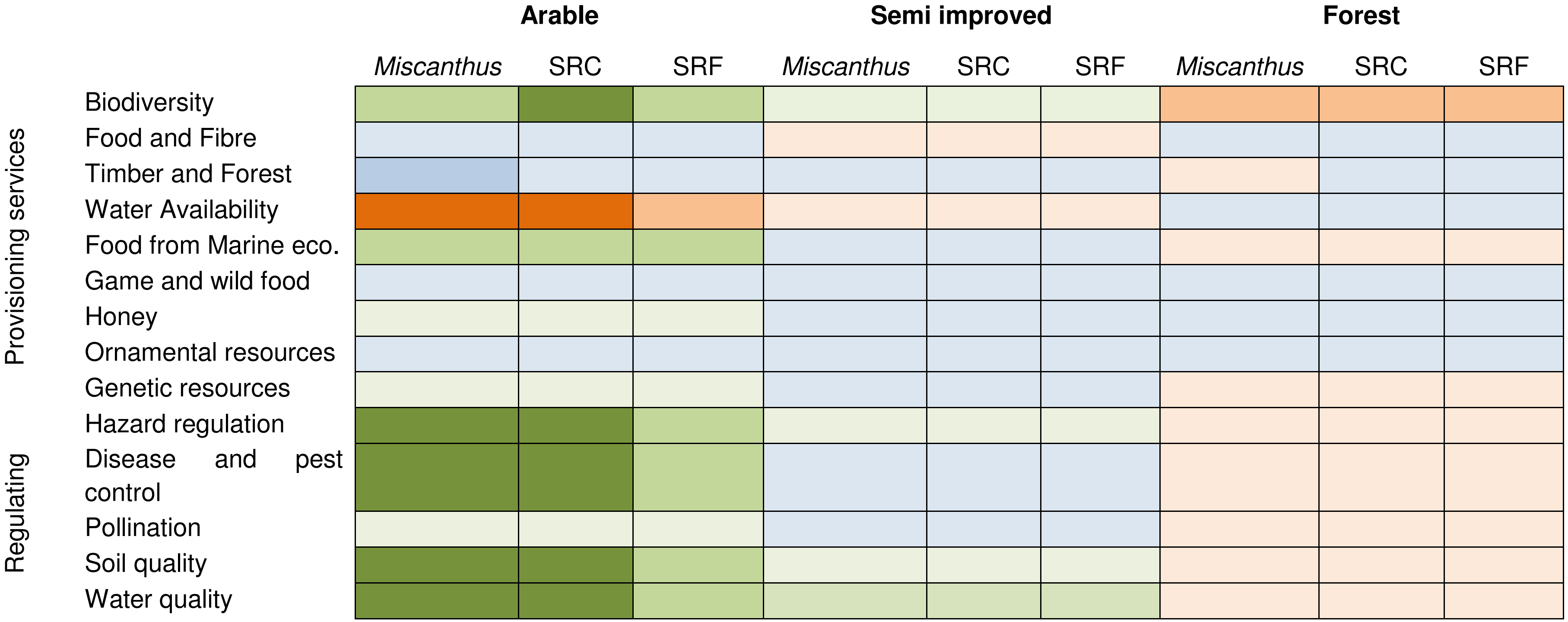
Based on dimensions of impact and strength of evidence, Table 4 summarises potential effects of land-use transitions on ecosystem service delivery in the UK for the most likely 2nd generation feedstocks. Impact was scored as negative, neutral or positive. A negative score indicating the transition would reduce, and positive increase, the provision of the service. A neutral score indicates little or no effect. For strength of evidence, high confidence was assigned where there was a well-developed literature indicating a clear understanding of change resulting from the transition. A medium confidence was assigned where there was a less well-developed literature but emerging evidence to understand the transition. Low confidence was assigned where there is little or no evidence. Full details of the assumptions that were made when producing this matrix are presented in Appendix A1.

Transitions from 1st generation crops to *Miscanthus* and SRC represent the most developed areas of research. We assigned strong confidence of a positive effect of this transition on hazard regulation (Section 4.5), disease and pest control (Section 4.6), soil (Section 4.8) and water quality (Section 4.9). It would be expected that mechanisms that serve to positively influence these services under transitions to *Miscanthus* and SRC would apply to SRF although we assign a medium confidence as the literature is less well-developed. We assign high confidence that *Miscanthus* and SRC can negatively impact water availability (Section 4.4) and medium confidence of a similar impact of SRF through the same mechanisms, although impact is contingent on local conditions.

For transition from semi-improved grassland we were unable to draw strong conclusions due to a lack of published literature. We scored two services as potentially decreasing: food and fibre - as semi-improved grassland is important for livestock production (Section 4.2); and water availability (Section 4.4) as the three transition crops exhibit high water-use. Three services were scored as increasing: hazard regulation (Section 4.5) principally through flood and erosion prevention in at-risk areas; soil quality due to increased porosity and litter input (Section 4.8); and water quality due to decreasing inputs of fertiliser (Section 4.9).

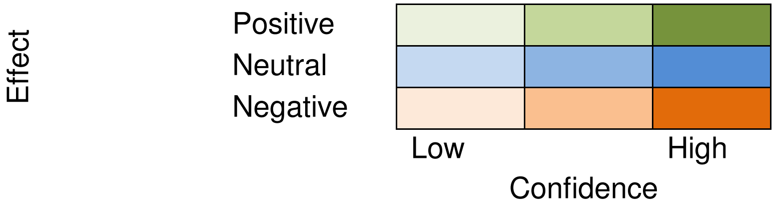
For transitions from forest we scored the majority of services as being negatively impacted due to the increased management intensity that the transition implies. However, it should be noted that negative impacts may be time-dependent, occurring mainly at establishment and harvesting. Compared to forest we would expect a continuum of increasing impacts from SRF to SRC to *Miscanthus* due to the shorter management cycles. In the UK it is unlikely that there will be widespread conversion of forest to 2nd generation bioenergy crops, however globally such conversion may have serious implication for ecosystem service delivery.

Table 4: Threat matrix of ecosystems service effects of transitions to differing bioenergy crops.



		Arable			Semi improved			Forest		
		Miscanthus	SRC	SRF	*Miscanthus*	SRC	SRF	*Miscanthus*	SRC	SRF
Provisioning services	Biodiversity	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
	Food and Fibre	🟦	🟦	🟦	🟧	🟧	🟧	🟦	🟦	🟦
	Timber and Forest	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟦	🟦
	Water Availability	🟧	🟧	🟧	🟧	🟧	🟧	🟦	🟦	🟦
	Food from Marine eco.	🟩	🟩	🟩	🟦	🟦	🟦	🟧	🟧	🟧
	Game and wild food	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Honey	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦
	Ornamental resources	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Genetic resources	🟩	🟩	🟩	🟦	🟦	🟦	🟧	🟧	🟧
Regulating	Hazard regulation	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
	Disease and pest control	🟩	🟩	🟩	🟦	🟦	🟦	🟧	🟧	🟧
	Pollination	🟩	🟩	🟩	🟦	🟦	🟦	🟧	🟧	🟧
	Soil quality	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
	Water quality	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧

KEY



Effect			
Positive	🟩	🟩	🟩
Neutral	🟦	🟦	🟦
Negative	🟧	🟧	🟧
	Low		High

Confidence

4. IMPACTS ON KEY ECOSYSTEM SERVICES

This report provides an abridged review under each of the key ecosystem services. For a more detailed review on each of these ecosystem services, the reader is referred to the accompanying series of appendices in a separate file.

4.1. Biodiversity

Biodiversity is key to the delivery of ecosystem services as it underpins the functioning of ecosystems (UK National Ecosystem Assessment, 2011). Despite much interest in the policy debate, there is a paucity of information examining links between bioenergy production and impacts on biodiversity. Much of the work that does exist is focused on terrestrial mammal, bird and pollinator species. In general our understanding of biodiversity impacts of bioenergy production on other taxonomic groups is poor and represents an area for future work. Two major reviews by Dauber *et al.* (2010) and Fletcher *et al.* (2011) found few studies examining the links between biodiversity and bioenergy crops globally. Dauber *et al.* (2010) in an extensive review focused on temperate systems identified 47 publications from nine European countries and the USA. Of these, the authors note that 22 contain findings based on five observations or fewer and that most were based on experimental plots raising the question of how readily results can be generalised to real systems. Fletcher *et al.* (2011) focused their review on four crops, corn (*Zea mays*), switchgrass (*Panicum virgatum*) together with *Pinus* and *Populus* species identifying only 15 studies examining land-use transitions to bioenergy production.

Studies report a positive effect on biodiversity for the transitions from 1st generation to 2nd generation bioenergy crops (Meehan *et al.*, 2010). This is attributed to management practices such as longer rotation times, reduced inputs of pesticides and fertilisers, greater spatial structure, better soil protection and winter harvesting period of the 2nd generation feedstocks (Dauber *et al.*, 2010, Donnelly *et al.*, 2011, Felten & Emmerling, 2011). For all transitions, impacts on biodiversity are likely to be related to factors such as overall management strategy, phase in the management cycle and local context and so could have both positive and negative impacts (Hardcastle, 2006, Lattimore *et al.*, 2009). For example habitat specialists will decline if the transition is to a crop with markedly different characteristics to their preferred habitat (Robertson *et al.*, 2011b, Robertson *et al.*, 2011c), conversely transitions to crops that are analogous to habitat that has been lost historically will exert a positive influence on regional biodiversity (Dahms *et al.*, 2010, Meehan *et al.*, 2010, Rowe *et al.*, 2011).

As overall regional diversity is driven by differences across the landscape (e.g. different crops/habitats, different stages in the management cycle), a strategy that promotes a range of habitats will exert a positive influence on regional biodiversity. To achieve maximum benefits, deployment of 2nd generation crops should be planned to take into account the relative biodiversity value of areas within the landscape (Dahms *et al.*, 2010, Rowe *et al.*, 2011) and unplanned piecemeal deployment of 2nd generation crops avoided (Dahms *et al.*, 2010, Robertson *et al.*, 2011a, Schleupner & Link, 2008).

Temporal dynamics of the bioenergy cropping system are also a key consideration that can influence biodiversity. The longer management cycles typical of 2nd generation feedstocks will benefit biodiversity, and for crops such as SRC and SRF there are likely to be changes in the value of the crop for species through the maturation phase (Dauber *et al.*, 2010, Riffell *et al.*, 2011). A number of studies report that the establishment and harvesting phases of 2nd generation bioenergy crops will have the most significant impact on species (Donnelly *et al.*, 2011). Introducing temporal diversity by harvesting bioenergy crops at different times will benefit species by creating reservoir from which they can recolonize areas at different stages in the management cycle (Dauber *et al.*, 2010, Rowe *et al.*, 2011).

4.2. Food, Fibre and Energy from Agriculture

The provision of food, fibre and energy through agricultural production is a key ecosystem service. However, the linking of food and energy markets that has arisen through policies to increase the production of bioenergy has caused significant problems, particularly for poorer sections of society. In the developed world the average consumer will tend to spend less than 10% of their income on food, whereas in the developing world this can be in excess of 50% (Pardue, 2010). As the prices of commodities fluctuate to meet competing demands for food and energy production, those sections of society which spend the highest proportion of their income on food are disproportionately affected. These market forces have contributed to starvation and civil unrest in parts of the world, with world hunger reaching a historic high in 2009 (Tirado *et al.*, 2010, Valentine *et al.*, 2012).

Within the ecosystem service framework there is little evidence for a reduction in the amount of crops produced, rather it is their final use that has changed. Our review found few studies that directly link bioenergy production with reductions in food or fibre production. Those that do exist are linked with government incentives to encourage farmers to switch production as a way of reducing GHG emissions. For example, Novo *et al.* (2010) details a loss of dairy farming in Sao Paulo state in Brazil driven by incentives for sugarcane production from the Brazilian government. Bryan *et al.* (2011) modelled the economic profitability of both food and biofuel agriculture under a number of carbon pricing and climate scenarios in the Murray-Darling area of Australia. Under baseline climate scenarios, a farm subsidy designed to promote GHG abatement through the production of bioenergy could lead to the loss of the most productive food-producing areas as it becomes economically more favourable for farmers to produce bioenergy crops. As a principal driving force behind adoption of 2nd generation crops is to decouple the food and bioenergy markets, such studies raise the question of whether policy incentives promoting 2nd generation feedstocks may impact food production as a result of conversion of existing crop land.

In the UK, studies suggest there could be considerable scope for expansion of 2nd generation crops without impacting food supplies. Aylott *et al.* (2010) found that by growing SRC on poor quality, marginal land an additional 0.8 million ha of land producing 7.5 million tonnes of biomass could be made available for bioenergy with limited impact on arable food production. Similarly, Lovett *et al.* (2009) concluded that growing *Miscanthus* on low-grade agricultural land in the UK would allow for production of 350,000 ha without a significant impact on food crops. However, based on production targets, rather than spare capacity, Sanderson and Adler (2008) demonstrate that 22.3 million ha of marginal land will be needed to meet targets for bioenergy by 2030 in the USA, creating direct competition with traditional forage-livestock production. The implications of this are explored by Ceotto (2008) who emphasise the role of marginal land in food production mediated through herbivores that transform low-quality plant proteins into meat and milk for human consumption.

Widespread conversion of marginal land for bioenergy production could exert considerable pressure on this sector of the food industry and would disproportionally impact those people occupying the socioeconomic margins (Findlater & Kandlikar, 2011).

One way to address competition for land and displacement of current agricultural activities is to develop methods that maximise production over the existing crop land, and identify areas for expansion that will have the least impact on the environment and society. There are a number of ways that this can be achieved, for example increasing yields of feedstocks through continued plant breeding and/or growing more stress tolerant feedstock cultivars that are resistant to disease and pests and have improved photosynthetic, nitrogen and water-use efficiencies (Clarke *et al.*, 2009). Simply identifying the most productive crops given the prevalent environmental conditions will result in increased yield without increasing the area of land used for production. For example, Qin *et al.*, (2012) modelled production of biofuel from corn, switchgrass and *Miscanthus* in the USA demonstrating that to produce an equivalent amount of ethanol would take 23.2 M ha, 25 M ha and 8.6 M ha respectively. This suggests that optimal selection of bioenergy crops could drive a reduction in land-use creating surplus capacity for food and fibre production.

4.3 Timber and Forest Products

It is estimated that wood and wood-derived bioenergy are the primary source of household energy for over half the world's population (Lattimore *et al.*, 2009, Talbot & Ackerman, 2009). The expansion of agricultural land into forested areas, coupled with increasing appropriation of timber for bioenergy production, has the potential to lead to a situation that parallels the current food vs. fuel debate. Raunikar *et al.* (2010), using a range of scenarios demonstrates that over the next 50 years increasing demand for timber (of which bioenergy production is one component), may lead to convergence of fuelwood and roundwood prices. The implications of this are stark: forest resources currently used for timber and paper production would begin to be appropriated for energy. This in turn would lead to increased extraction impacting the health of forest systems, and reducing the availability of the primary source of household energy of particular importance for the world's poorest people. Indeed, Lattimore *et al.* (2009) considers that such global supply chain issues will, in the absence of regulatory frameworks designed to protected people in less developed areas, be one of the principal impacts of increased use of forest resources for the production of bioenergy.

As the impact of bioenergy production on timber and other forest products will primarily be driven by economic factors, management of the global resource will be key. From this perspective, plantation forestry can play a significant role in ameliorating impacts of bioenergy production and securing the provision of timber and other forest products in the future. As discussed by Talbot and Ackerman (2009), plantations are designed to provide easy access for harvesting and removal and are managed for productivity; as such they have an inherently higher capacity to provide biofuel and timber products. However, Lattimore *et al.* (2009) considers that the increased intensity associated with shorter rotation periods of 2nd generation crops from SRC and SRF, and the shift from removal of only traditional products such as saw logs and pulpwood to a higher proportion of the forest biomass is likely to significantly impact forest systems and by extension the ecosystem goods and service that they provide.

4.4 Water Availability

The impact of 2nd generation bioenergy crop production on water availability will be dependent on type of crop, location and management practices (Gopalakrishnan *et al.*, 2009, Yang *et al.*, 2009). As commercial scale production of 2nd generation crops is rare in regions where 1st generation crops are planted (VanLoocke *et al.*, 2012) there is little empirical evidence to understand impacts at commercial scales. However, the characteristics of 2nd generation bioenergy crops such as *Miscanthus*, SRC and SRF mean that they will likely have a negative impact in water resources. For example although *Miscanthus* has been demonstrated to possess a water use efficiency (WUE) similar to 1st generation feedstocks (Anderson-Teixeira *et al.*, 2009, Hickman *et al.*, 2010, VanLoocke *et al.*, 2012), it is characteristed by a higher evapotranspiration rate due to a large root system, high leaf area index, long growing season and strong coupling with the atmosphere due to its height (Finch & Riche, 2010, Le *et al.*, 2011). Although high WUE is desirable in conditions where water is not a limiting factor (VanLoocke *et al.*, 2012), the higher absolute requirements of 2nd generation crops mean they can have a significant negative impact where water resources are limited.

Intensity of production will have a significant influence on water resources. Assuming uniform production across the landscape Vanloocke *et al.* (2010) demonstrate that replacement of 10% of US agricultural land with *Miscanthus*, leading to production capacity sufficient to meet government targets for bioenergy production (Heaton *et al.*, 2008), would have little or no effect on the hydrological cycle. In reality the production of bioenergy from feedstock such as SRC, SRF or *Miscanthus* is likely to only make economic and energetic sense if production is clustered around biorefineries (Kocoloski *et al.*, 2011, Vanloocke *et al.*, 2010). In this instance, conversion of 25% (in water stressed areas) to 50% (in all remaining areas) of existing land cover to *Miscanthus* would have a severe impact on hydrological cycle (Vanloocke *et al.*, 2010).

Impacts on water resources will manifest themselves primarily during the growing season, consistent with increased evapotranspiration, so are contingent on seasonal patterns in water availability within the landscape (Lattimore *et al.*, 2009, Oliver *et al.*, 2009, Stone *et al.*, 2010). Richter *et al.* (2008) using a network of 14 field trial sites across the UK, developed an empirical yield model for *Miscanthus* that demonstrated a strong link between soil-available water content, precipitation and *Miscanthus* yield. The Richter *et al.* (2008) model suggests that a 40% reduction in yield may arise if the crop is subjected to summer drought. For this reason trade-offs between conservation of water resources and biomass production will play an important part in determining the suitability of production in a specific area. Assessing water resource availability should be a major criteria in determining production areas (Ajanovic, 2011).

4.5 Hazard Regulation

Two interlinked regulating processes can be considered under hazard regulation: firstly the control of erosion by wind and water, and secondly flood risk regulation. Boardman and Evans (2006) report a strong link between changing agricultural practices and water driven erosion. Although dependent on environmental context and stage in the management cycle, 2nd generation crops such as *Miscanthus* (Wilson *et al.*, 2011, Wu & Liu, 2012) and SRC or SRF (Busch, 2012, Lattimore *et al.*, 2009, Updegraff *et al.*, 2004) would be expected to enhance erosion control compared to 1st generation crops. Second generation crops require no annual tillage, provide year round soil cover and exert a positive influence on many soil properties including the improvement of water fluxes resulting in a reduction in surface runoff (Blanco-Canqui, 2010) and wind erosion (Busch, 2012).

These benefits have a strong temporal element linked to the length and stage of the management cycle. Land conversion that increases the length of the cycle, as would be the case for transitions from 1st generation to 2nd generation feedstocks, would likely enhance hazard regulation. Conversley land-use change that shortens the management cycle would likely reduce the provision of this service. As such, production of 2nd generation crops may be less effective at controlling erosion and providing slope stability than long term forest management (Schulze *et al.*, 2012), indicating such transitions should be avoided in erosion prone areas.

4.6 Disease and Pest Regulation

A diverse range of habitats within the landscape promotes predators and parasitoids including arthropods, birds and mammals together with microbial pathogens, all of which reduce the pressure exerted on crops by pest species (Power, 2010). Meehan *et al.* (2011) provides strong evidence for a link between pest pressure and landscape simplification in mid-west USA using an index based on insecticide application. Their study established that pesticide application increased with increasing proportion and patch size of cropland and decreased with increasing proportion of semi-natural habitat. The authors report that the financial implications of this finding are considerable and range from $34 million to $103 million in direct costs, with indirect costs in terms of environmental degradation likely to be at least double this. Similarly Landis *et al.* (2008) demonstrate that increasing corn production in the USA led to a drop in biocontrol services worth $58 million per year. Strategies that enhance natural pest and disease regulation can therefore realise significant financial and environmental benefits.

Using a meta-analysis of 27 studies, Bianchi *et al.* (2006) report evidence of enhanced activity of natural enemies associated with the presence of herbaceous and woody habitats within the landscape. This suggests that transitions from 1st to 2nd generation crops could enhance pest control services as part of a diverse agricultural landscape. Rowe *et al.* (2011), in one of the few studies to systematically examine the effect of commercial 2nd generation bioenergy plantations on biodiversity, demonstrated an increase in the number of Hymenoptera and large Hemiptera, the presence of which would likely enhance predation of pest species. Similarly, in a comparison of corn and prairie grassland systems Werling *et al.* (2011) reported significant benefits for the grassland systems including a two orders of magnitude increase in enemy biomass, a fourfold increase in the number of predator families and a tripling of predation on eggs of pest species in the grassland system.

Such evidence suggests that a mix of bioenergy crops together with traditional row crops could enhance pest and disease regulation. This effect will manifest itself not only through the increase in diversity or predators but also as 2nd generation crops will provide a source for re-colonisation of food crops by enemies following application of chemicals or harvesting (Thomson & Hoffmann, 2011). Werling *et al.* (2011) found that enemy biomass and diversity within food crops peaked at intermediate levels of forb cover within the landscape. This suggests that relatively modest amounts of 2nd generation bioenergy crops within the landscape could provide maximum benefit for co-occurring row crops.

4.7 Pollination

Globally it is estimated that insect-provided pollination services are worth over $200 billion dollars per year (Vaknin, 2011); with around 84% of crop production in Europe (Gallai *et al.*, 2009), and 60% globally (Klein *et al.*, 2007) dependent on this service. Pollination services are of value both for pollination of commercial crops including food crops such as fruit, bioenergy crops and for non-commercial plants that contribute to other ecosystem services such as the maintenance of plant diversity and primary production (Carvell *et al.*, 2007, Kremen *et al.*, 2007, Potts *et al.*, 2009, Smith *et al.*, 2011).

A principal driver of loss of pollinators is homogenisation of the landscape (Holzschuh *et al.*, 2007, Steffan-Dewenter & Westphal, 2008). As with disease and pest regulation, conversion of existing land use from 1st generation to 2nd generation bioenergy crops will create a diversity of habitats within the landscape and may enhance pollinator diversity. This effect is associated with factors such as longer rotations times, different understory vegetation, increased diversity of nectar and pollen sources and provision of nesting and overwintering resources (Carvell *et al.*, 2007, Holzschuh *et al.*, 2007, Klein *et al.*, 2007, Kremen *et al.*, 2007, Rowe *et al.*, 2011).

4.8 Soil Quality Regulation

Compared to 1st generation bioenergy crops, both the characteristics of 2nd generation crops (e.g. deep root systems, high litter input) and the management practices (e.g. less maintenance, longer harvesting cycles) convey significant benefits on soil quality. These include reduced bulk density, improved soil porosity, improved microbial activity and biomass, improved macro-invertebrate populations, improved soil organic matter (SOM) levels and improved fluxes of water, air and heat (Blanco-Canqui, 2010, Haney *et al.*, 2010, Pellegrino *et al.*, 2011). Such benefits contribute to the effective delivery of other ecosystem services such as carbon storage and flood prevention, suggesting significant benefits from the adoption of 2nd generation crops.

Benefits for soil quality accrue through the longer management cycles associated with 2nd generation bioenergy crops. However, a number of authors note a distinct temporal phases in the relationship between feedstock production and soil quality parameters. For example during the transition phase from grassland to *Miscanthus*, Donnelly *et al.* (2011) reported negative impacts on soil structure associated with ploughing and lack of ground cover. Similarly, Lattimore *et al.* (2009) reports a reduction in SOM associated with harvest in SRF. Such negative impacts are short-lived and only relevant at specific phases in production. Indeed over the long-term, transitions to 2nd generation crops on marginal lands serve to improve soil quality by increasing infiltration rates, increasing SOC and preventing erosion and, at the extreme, can be used as a phytoremediation strategy to rehabilitate contaminated land (Blanco-Canqui, 2010).

4.9 Water Quality

Agricultural production can significantly impact water quality through a number of different pathways, including input of agrochemicals and sedimentation. In general the lower requirement for fertiliser coupled with high water uptake and continuous ground cover preventing sediment loss suggests that 2nd generation crops could deliver significant benefits for water quality. For example 2nd generation crops could be an effective management tool if deployed as buffer strips surrounding traditional row crops (Gopalakrishnan *et al.*, 2012) or in nitrate-vulnerable zones (Dimitriou *et al.*, 2012).

A key consideration for water quality is fertiliser application rates (Sanderson & Adler, 2008). Modelling studies of *Miscanthus* indicate benefits in terms of reduction in nitrate loss to aquatic system can be realised at application rates of 80-100 kg-N/ha (Ng *et al.*, 2010); however, as rates increase impacts become comparable to those of 1st generation crops (Wu & Liu, 2012). For SRC, Gonzalez-Garcia *et al.* (2012) report that 87.5% of nitrate emissions can be attributed to application of fertiliser, although losses from forestry system such as SRC and SRF are lower than those from 1st generation crops (Callesen *et al.*, 2011, Dimitriou *et al.*, 2012, Syswerda *et al.*, 2012). From a management perspective, there are likely to be trade-offs between water quality benefits and yield for 2nd generation crops (Gonzalez-Garcia *et al.*, 2012, Ng *et al.*, 2010, Wu & Liu, 2012) so understanding how to balance these will be key to delivering water quality benefits.

As with other services, a number of studies report a distinct temporal element to the benefits of 2nd generation crops with concentrations of agrochemical released into aquatic system fluctuating through time as a function of application timing, amount and environmental conditions (Love *et al.*, 2011, Syswerda *et al.*, 2012). In SRC and SRF, establishment and harvesting have negative impacts on water quality compared to the growth phase (Dimitriou *et al.*, 2012, Lattimore *et al.*, 2009), with Gonzalez-Garcia *et al.* (2012) attributing 25% of the total eutrophication potential to establishment and 50% to harvesting in a non-fertilised scenario.

4.10 Additional Services

In the appendix to this report we consider 2nd generation bioenergy impact on a range of other services. In most cases these were services where there was little information available or where there was thought to be only a minor impact. Appendix A3.4 details an additional six provisioning services; Food from Marine Ecosystems, Game and wild-collected food, Honey, Peat, Ornamental Resources and Genetic resources. Appendix A5 provides an overview of supporting services and appendix A6 considers cultural services.

5. BIOENERGY CROPPING AND INDIRECT (ILUC) IMPACTS

Background

There is a general consensus that for 2nd generation bioenergy cropping systems, GHG emissions are reduced, relative to fossil fuel equivalents (The Royal Society, 2008), however, the magnitude of this saving varies widely. This partly reflects the emphasis placed on LCAs that use generic values for many parts of the bioenergy chain with reference to limited empirical data. Many analyses of bioenergy chains are also system-bound and do not consider indirect or consequential effects of the land-use change associated with the energy crop and it has become clear that such iLUC effects may be significant, but difficult to quantify. Genuine carbon reductions associated with a switch to bioenergy are captured in the first of four principles in the UK Bioenergy Strategy (Department of Energy and Climate Change, 2012) and thus provide a significant technical and policy challenge to which the UK is committed. The strategy recognises the complexities in quantifying the carbon balance of bioenergy cropping systems, with one of the most difficult issues being the impact that they may have through indirect land-use change (iLUC). Here we define iLUC as the use of land to grow bioenergy crops that displaces food crops to another location, or has an impact on provisioning ecosystem services (food, feed, fibre, water). The displacement may result in food-crop growth on land with a high carbon stock, such as forest or wetland (Gawel & Ludwig, 2011). Given the nature of bioenergy feedstock growth, with international trade and global markets, it is likely that iLUC will often occur across national and wide geographical boundaries. iLUC was first brought to the attention of policy makers in 2008, when Searchinger *et al.* (2008) and Fargione *et al.* (2008) suggested that iLUC could effectively remove any GHG benefit of the switch from fossil fuels to biofuels; however, this is a controversial debate where methodological limitations make true quantification of iLUC difficult, given a range of crops, soils and environmental conditions. In addition, LUC and iLUC occur for a variety of reasons not always associated with bioenergy cropping. Indeed it is considered that bioenergy may not be the largest land-use change with an indirect impact, but that food-crop displacements may be of a greater magnitude in future. A final problem with iLUC impacts is that they extend beyond those of the GHG balance, since iLUC may have effects on biodiversity, social and water rights.

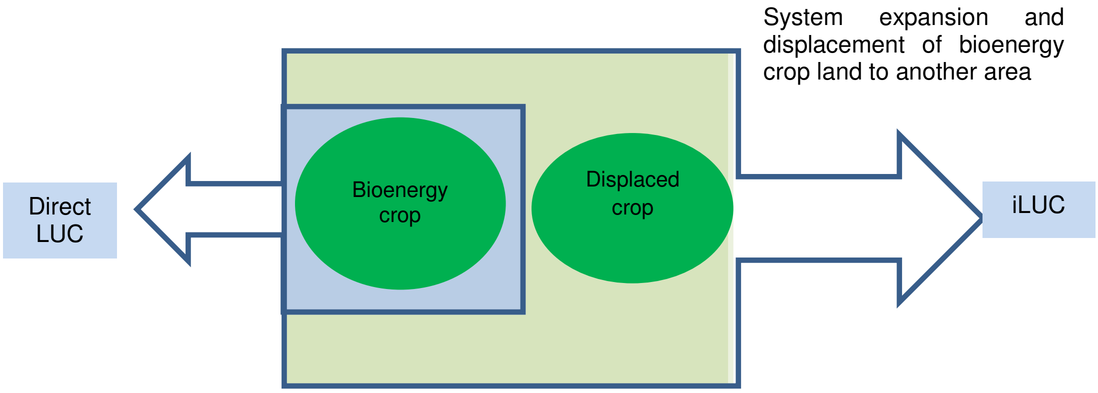


Figure 1: General principle on indirect land-use change following expansion of the bioenergy cropping system

The emissions associated with iLUC are inherently uncertain and difficult to quantify (Department of Energy and Climate Change, 2012). They cannot easily be monitored, but only modelled, and the current models have significant limitations. Several modelling approaches must be coupled in order to make an iLUC calculation – economic, biophysical and technical – and this has rarely been achieved. One major limitation is data availability: for example, direct LUC data for bioenergy GHG emissions. No adequate methodology has been agreed to-date on how to quantify iLUC. Despite this there is a clear certainty that iLUC contributes additional GHG emissions, over and above those where iLUC is not quantified and it is now considered likely that these effects may be significant and more important for biofuel (liquid fuel) chains rather than those for heat and power (Gawel & Ludwig, 2011). At the technical level, quantification of the iLUC impacts and their implementation into policy remains a difficult and unresolved area. However, recent advances in Europe have moved forward in developing a directive (described below) for bioenergy feedstock use in Europe. The summary is that policies that control, reduce and offset iLUC impacts are possible, but the complexities of this issue have yet to be adequately resolved.

Methodological Approaches

A number of methodological approaches have been proposed to deal with iLUC over the past five years (Bauen *et al.*, 2010, Fritsche *et al.*, 2011, Gallagher, 2008, Gawel & Ludwig, 2011, Hiederer *et al.*, 2010). The Fritsche *et al.* (2011) publication for the European Parliament summarises the three studies commissioned by the European Commission during 2009-2010, that were aimed to develop a methodological approach for the EU to deal with iLUC in an appropriate way - one undertaken by IFPRI, and two by JRC. However, the key findings were that each of these studies, although valid, had methodological limitations. The main problem remains that for iLUC to be quantified, different modelling approaches must be coupled. Firstly, global economic models are used to estimate changes in land-use associated with bioenergy crop production. For example, computational general equilibrium models (CGE) are one such approach. They simulate future market response to increased bioenergy demand using equations to describe the equilibrium state for global trade. The base-line scenario may be compared with different scenarios that predict future increases in bioenergy demand and the model then determines the increased land-use required to fulfil this demand. Such models are comprehensive but highly aggregated, and are not transparent in their assumptions and equations. Partial equilibrium models (PE) are similar, but can focus on smaller regions of the globe, freezing global interactions defined from the broader CGE models, and therefore offering increased resolution. Causal-descriptive and deterministic models are a different type of modelling approach entirely: they use a bottom-up approach to describe particular supply chains from known or predicted data. Although they lack the comprehensive global scope of CGE and PE, they may be valuable for distinctive analysis of small sectors of the bioenergy market.

Coupled to these economic models, any estimation of iLUC must also determine the GHG emissions of the land-use systems in question. Thus, the carbon content of the land prior to and after change to bioenergy must be known. High level IPCC default data are the most likely route for obtaining such data, and these are generally modelled outputs. However, they rely on a detailed understanding of the land-use type and for this, high-resolutions maps (very high resolution in some instances) must be available to make the calculation.

Finally, for 2nd generation bioenergy crops, only limited empirical data have ever been made available to check IPCC assumptions and this is a significant limitation of this approach (Smith *et al.*, 2012).

Once the land-use associated GHGs have been calculated, the 'whole chain' carbon cost of the crop should be quantified, determined largely by end-use of the feedstock, for example biodiesel, bioethanol, heat or power. The difficulty here is that this is a very data-intensive activity where information is fed into the calculation for whole LCA of the crop in question and significant limitations are associated with these analyses. For example, the emissions of GHGs or carbon equivalents from N_2O are largely unknown for 2nd generation crops, although as reports emerge, is appears that these could be significant (Zona *et al.*, 2013) and certainly, N_2O was identified by Rowe *et al.*, (2011) as an important contributor to whole life-cycle GHG balance in bioenergy systems. Other unknowns are also apparent, in particular the treatment of co-products within the whole life-cycle and where the 'system boundary' is drawn. As described by Whittaker et al. (2010), there are three approaches that may be used to calculate co-product credits for LCA studies: energetic allocation, economic allocation and system expansion. In the first two approaches, the energy or GHG emissions are allocated between the main product and co-product by energy content or economic factors. In system expansion, the energy or GHG derived from the co-product is added to the analysis and may significantly change the GHG 'cost' of the system. Common co-products include DDGS – an important feedstock for cattle and glycerine from biodiesel production. The way in which co-products are dealt with in the LCA can be significant for the overall GHG balance, and thus adds another layer of uncertainty to the iLUC calculation.

This set of processes required for an accurate iLUC calculation gives an insight into the complexities of policy development, since the science and technology is still in the 'discovery' phase of coupling complex models with many limitations and inadequacies. Against this background, the European Parliament commissioned a series of reports (IFPRI and two JRC reports) to provide insight into iLUC, and national Governments and international organisations have followed these reports with studies of their own. Most notably for the UK, The Gallagher Report (Gallagher, 2008), The Dutch Environmental Agency (PBL, 2010), the E4Tech study for DfT (E4Tech, 2010) and the Oeko-Institut's iLUC Factor Approach (OEKO, 2010). For global governance, The European Environment Agency (EEA, 2008), the USA Environmental protection Agency (US EPA, 2010), The Global Bioenergy Partnership (GBEP, 2011), The International Energy Agency (IEA, 2010), the Organisation for Economic Cooperation and Development (OECD, 2009), and United National Environment Programme (UNEP (United Nations Environment Programme)/RSB (Roundtable on Sustainable Biofuels)/IPIEACA (International Petroleum Industry Environmental Conservation Association), 2009), have all reported on this important topic. In the UK, The Bioenergy Strategy (Department of Energy and Climate Change, 2012) and The Committee for Climate Change (Committee on Climate Change, 2011) have also been active on this topic.

Given the range and number of approaches relevant to the issue of iLUC, it is nevertheless possible to make some generalisations about the magnitude of iLUC impacts. In addition to the figures in Table 5, the reader is referred to the GBEP (2011) report for a full comparison of contrasting iLUC data from several different modelling and scenario analyses. Below are the output data for a single modelling activity, but they have been highlighted since they consider, in one of the few iLUC studies, 2nd generation crops in the form of SRF (short rotation forestry) transitions.

The data represent a simplified iLUC approach developed by Oeko-Institute, based on statistics and risk. It relies on being able to predict GHG emissions from current land-use types and assumes too that the near-future patterns of global trade in agriculture can be assumed from trade trends. In addition to calculation, the approach ascribes a ‘risk’ level to the output – how likely it is that one ha of displaced crops will lead to land-use change as an accompanying effect. Generally, a 25% risk is seen as most likely, at least to 2020. The data are interesting as they highlight both positive and negative effects of iLUC depending on crop type and land-use transitions relative to fossil fuels, but that in general, diesel-based chains are worse than ethanol for iLUC and that SRF is extremely good. No analysis was run for perennial grasses.

Table 5: OEKO model output for a range of crop types and transitions for LCA, plus LUC (dLUC) plus iLUC, with a 25 or 50% ‘risk’ factor.

	GHG emission g CO$_2$eq/MJ$_{biofuel}$				**Reduction vs. fossil fuel**			
Region, feedstock,	**LCA**	**+dLUC**	**+iLUC 25%**	**+iLUC 50%**	**LCA**	**+dLUC**	**+iLUC 25%**	**+iLUC 50%**
Biodiesel options								
EU, rapeseed,	40	40	73	107	-54%	-54%	-15%	**24%**
EU, rapeseed,	40	67	100	134	-54%	-23%	**16%**	**55%**
EU, SRF*, arable	14	-2	36	75	-84%	-103%	-58%	-14%
EU, SRF*, grass	14	29	67	106	-84%	-67%	-22%	**22%**
AR/BR, soy, grass	20	51	92	118	-76%	-41%	**7%**	**37%**
AR/BR, soy, sav.	20	188	188	188	-76%	**118%**	**118%**	**118%**
ID, oil palm, grass	43	12	30	48	-50%	-86%	-65%	-44%
ID, oil palm, degr.	43	-55	-55	-55	-50%	-163%	-163%	-163%
ID, oil palm, forest	43	213	213	213	-50%	**147%**	**147%**	**147%**
Ethanol								
EU, wheat, arable	45	45	79	112	-46%	-46%	-7%	**32%**
EU, wheat, grass	45	72	106	139	-46%	-15%	**24%**	**63%**
BR, sugarcane,	26	26	47	68	-69%	-70%	-45%	-20%
BR, sugarcane,	26	43	64	85	-69%	-50%	-25%	**0%**
BR, sugarcane,	26	-1	-1	-1	-69%	-101%	-101%	-101%
BR, sugarcane,	26	120	120	120	-69%	**41%**	**41%**	**41%**

Source: OEKO (2010) and reproduced by Fristche et al (2011, European Parliament); fossil comparators from EU RED; positive (bold **in red**) figures indicate that no emission reduction is achieved but **an increase**; *= short-rotation forestry as feedstock for BtL (Fischer-Tropsch diesel); AR= Argentina, BR= Brazil; sav.= savannah; degr.= degraded land; grass= grassland (pasture).

Conclusions on iLUC in the context of the UK: food versus fuel?

With respect to the UK, our main concern is the use of ‘food land’ for the deployment of bioenergy crops, since this has the potential to initiate a chain of events that result in land displacement and iLUC. Given the context of ELUM, here we consider only 2nd generation crops – *Miscanthus* and willow/poplar SRC since these are the two most likely land-use changes to bioenergy that will occur beyond 2020, when the policy environment for further 1st generation crop expansion will be limited. Thus, biodiesel from OSRC and the use of wheat-grain for fuel are not considered.

The total amount of agricultural land in the UK is 18.26 Mha and it has been estimated that the theoretical maximum available land for bioenergy is likely to be between 0.93 and 3.63 Mha in England and Wales (Department of Energy and Climate Change, 2012). Two peer-reviewed reports have considered how this limited land resource might be deployed for 2nd generation bioenergy crops in England and Wales, with minimum competition for food land, whilst two pieces of restricted and as yet unpublished data also exist – the first from the ETI BMVC project and the second from the UKERC Spatial mapping of energy crops and input-output modelling. These pieces of work are moving towards a consensus, and a recent workshop held at The University of Southampton brought the findings together in order to make some critical evaluation of how much bioenergy could be deployed without a significant impact on likely food production in the UK. Work by Aylott *et al.* (2008) and Aylott *et al.* (2010) estimated that 0.8 M ha of land could be used for 2nd generation bioenergy SRC that was poor quality or marginal land, where high quality arable land of agricultural land classes 1, 2 and 3 were avoided. This study revealed the preference of SRC to be grown in the North West and South West when high-quality arable land was removed from the supply potential (see Figure 2).

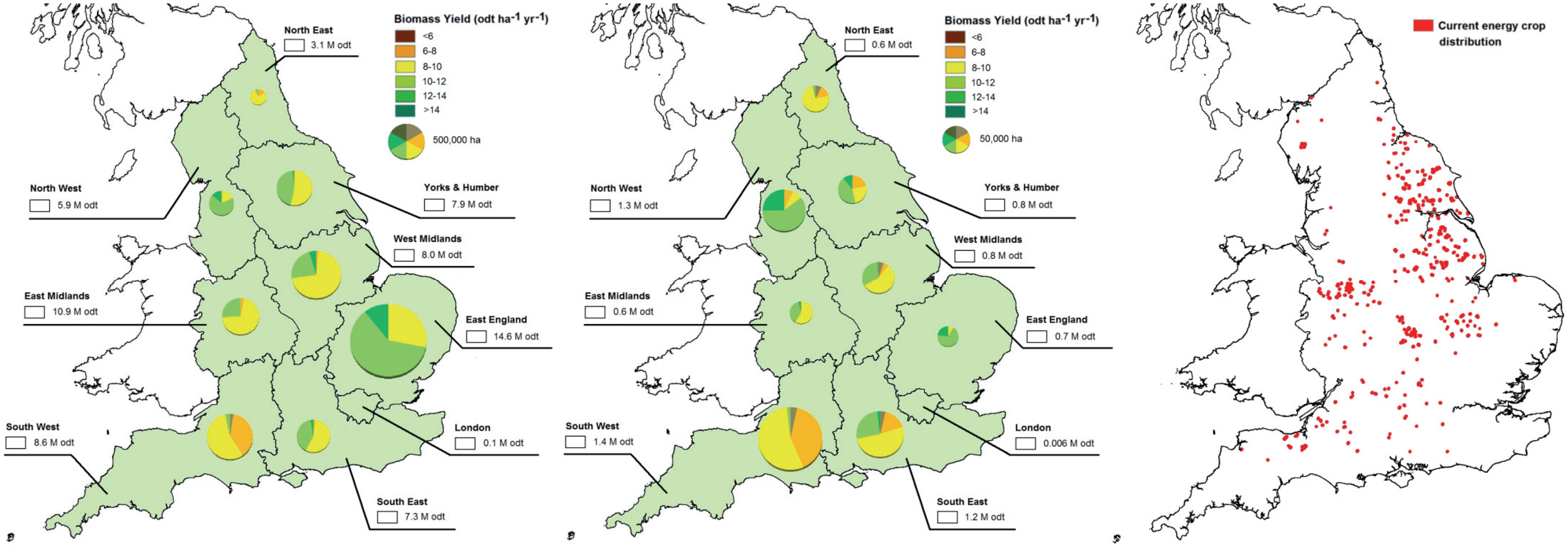


Figure 2: Spatial production maps for England. (A) Estimated yields of short-rotation coppice [SRC] (oven-dry tonnes ha-1 year-1) when displacing all available land; **(B)** estimated yields of SRC when displacing Agricultural Land Classification (ALC)5 and the most productive 97 % of ALC4; and **(C)** current energy crop distribution, based on Energy Crop Scheme Agreements prior to March 2009 [106]. Estimated yields exclude land fully or semi-restricted land for planting energy crops. Taken from Aylott et al., (2010).

In a similar study, Lovett *et al.* (2009) developed constraints maps for *Miscanthus* and working to supply 350,000 ha, determined that the most likely regions for *Miscanthus* growth would be the South East of England, South West and West Midlands, thus providing some complementarity alongside the increased deployment of SRC willow/poplar. In general, both of these studies support the notion that in the UK, up to 1 M ha of poor-quality agricultural land, with agricultural land classes of 4, 5 and some 3 (avoiding agricultural land classes 1 and 2 for prime arable, food crops) could be available for 2nd generation deployment in the UK. These studies focus on England and Wales with no consideration of Scotland, which would provide an additional resource for woody crops, including SRC willow and poplar. Our unpublished work develops these approaches further, with improved constraint-map analysis and consideration of the whole of Great Britain, and now with data out to 2050 in the light of climate change. Although this analysis is still on-going, in general it confirms that up to 1 M ha of land could be available in the UK without displacement of food crops. However, this technical potential may never be realised since it is poor-quality land, often sloping or with difficult access, poor soil and limited ability to generate profit. These considerations are beyond the scope of this review. In summary, we conclude that in the UK, with the move to 2nd generation non-food crops, it will be possible to identify up to 1 M ha of land for bioenergy crop growth that has no significant impact on food crops and does not therefore lead to iLUC. If planted, this has the potential to supply more than 5% of UK electricity demand, or to be utilised in a range of bioenergy technology options as identified in BMVC modelling. However, sustainability criteria will need to be carefully developed, alongside policy incentives, if this increased planting is to occur appropriately or at all in the UK.

Main findings from the regulatory agencies and global governance initiatives

USA EPA

The USA Environmental Protection Agency has worked during 2008-2010 to develop an iLUC standard as part of its National Renewable Fuel Standard Programme (RFS). This takes a similar approach to the EU regulatory framework and demands a 20% GHG emissions improvement on any bioenergy feedstock chain compared to the 2005 GHG emissions of the equivalent fossil fuel chain. This base-line target is ramped up, again in a similar way to EU, but in the case of USA this depends on feedstock type. In the USA, iLUC has been added to assessment in 2010 although additional analysis is currently on-going. Of particular note in the USA is the Californian Low Carbon Fuel Standard (CLFS) that now also includes an iLUC approach. The approach for iLUC is the use of an iLUC factor depending on crop type, with ‘look-up’ tables to identify iLUC factors specific to fuel and crop types. The Californian iLUC emissions for bioenergy chains range from 30 gCO_{2eq}/MJbiofuel for ethanol from USA corn, 46 gCO_{2eq}/MJbiofuel for ethanol from Brazilian sugar cane to 62 gCO_{2eq}/MJbiofuel for soybean biodiesel, again confirming higher iLUC factors for biodiesel compared to bioethanol crops. Under this scenario, all crops performed better than gasoline with the exception of ethanol from corn, since this had large LUC emissions driven by agricultural inputs.

IEA Bioenergy

A number of Bioenergy Tasks within the International Energy Agency deal with GHG emissions, in particular Task 38 on GHG emissions but also Task 40 on international trade. IEA is unusual in that the technology roadmap published for bioenergy, which highlights the emerging 2nd generation crops, has been utilised in future scenario development for LUC and iLUC GHGs associated with bioenergy. The most important finding is that in several scenarios run out beyond 2030, where 2nd generation crops begin to dominate, then all outputs produced show a net reduction in GHG emissions relative to both bioethanol and biodiesel. IEA confirms the important point that lignocellulosic feedstocks can be used in an integrated manner for more productive land, where food and fuel crops together make land more productive and 2nd generation crops are targeted for marginal land-use.

Global Bioenergy Partnership, GBEP

GBEP is a partnership of 23 countries and 14 international organizations and probably now represents the strongest group for global governance of bioenergy sustainability issues. Non-government partners include IEA, UNEP and FAO. Three tasks forces work alongside each other on Sustainability, GHG methodologies and Capacity Building. GBEP published a report on iLUC in November 2011, highlighting the inadequacies of the iLUC Factor approach, highlighting the relatively small EU market for many members, relative to the rest of the world, and questioning the necessity for further legislation on biofuel sustainability. The report emphasised the positive impacts of biofuel crop deployment that could be optimised: for example, better use of co-products, yield increases, system integration (in agreement with IEA) and the faster introduction of 2nd generation crops. However in 2011, GBEP commissioned a new report undertaken by Ecofys (GBEP, 2011), that summarised the modelling approaches currently being considered for iLUC, reiterating the importance of crop type, future yield enhancement, co-product handling and underlying assumptions of the models. This detailed analysis of model output is of value, but beyond the scope of this report.

UK Bioenergy Strategy and Committee on Climate Change Bioenergy Review

The UK Bioenergy Strategy did not consider iLUC in any greater detail than the report summarised here, since EU legislation did not, at that time, incorporate iLUC into policy. DECC remains committed to the delivery of an integrated bioenergy calculator that considered land-use change and most importantly, this should consider the deployment of 2nd generation crops in the context of iLUC in future; work is ongoing to achieve this. The Committee on Climate Change (CCC) report on Bioenergy concluded that although energy from biomass was currently small in the UK, that this had the potential to increase in all sectors. The consideration given to iLUC is now largely superseded by the EU 2012 Directive, and as with the DECC Bioenergy Strategy, the main focus only considered the outputs of the IFPRI modelling approach, with no data on 2nd generation crops. The relevance of this study to ELUM and moving forward is therefore limited.

The current EU policy directive

In October 2012 in the context of the EU, the iLUC debate was brought to a conclusion when a new proposal for a directive (European Commission, 2012) was eventually issued from the European Commission, following an extensive consideration of the scientific evidence and review of the limitations currently associated with modelling approaches. The proposal is to reduce the limit on the use of food crops to fulfil the Renewable Energy Directive (RED) from 10% biofuel-based fuels to 5%. This is to stimulate the use of 2nd generation non-food bioenergy crops and also to encourage the use of waste and straw for bioenergy conversion.

For the first time in Europe, the iLUC effects of bioenergy chains must now be considered, at least for their GHG impacts. The proposal is to amend the RED and Fuel Quality Directives so that:

- Minimum GHG savings threshold is increased from 35% to 60% after July 2014, in order to improve the efficiency of biofuel production as well as discourage further investment in installations with low GHG performance.
- To utilise iLUC factors in reporting fuel supplies for GHG emissions. The iLUC impact of cereals was given as 12 gCO_{2eq}/MJ, for sugars 13 gCO_{2eq}/MJ and for oil crops 55 gCO_{2eq}/MJ. The iLUC factor for 2nd generation grasses and trees was set at zero, although LUC factors still apply to these crops, particularly if converted from forest, grassland, wetlands and other high-carbon, pristine soils.
- To limit the amount of food-crop based biofuels and bioliquids that can be counted towards the EU's 10% target for renewable energy in the transport sector by 2020, to the current consumption level, 5% up to 2020, while keeping the overall renewable energy and carbon intensity reduction targets.
- To provide market incentives for biofuels with no or low indirect land-use change emissions, and in particular the 2nd and 3rd generation biofuels produced from feedstock that do not create an additional demand for land, including algae, straw, and various types of waste, as they will contribute more towards the 10% renewable energy in transport target of the Renewable Energy Directive.

The Commission will report back in 2017 on the latest scientific advice on the effectiveness of this Directive, and report on both the iLUC factors effectiveness and the incentivisation of 2nd generation and non-food biomass feedstocks.

6. CONCLUSIONS AND FUTURE WORK

Tilman *et al.* (2009) argues that if society is to realise the potential benefits of bioenergy a key requirement is that science-based safeguards must be introduced to ensure that the best feedstocks and practices are adopted. This review demonstrates a knowledge gap that, for some land-use transitions, prevents us from fully understanding the effect of increased production of 2nd generation crops. This hinders our ability to select the best feedstocks and employ the optimum management practices to safeguard ecosystem services in the face of policy that will drive the expansion of 2nd generation production over the next decade.

Our most complete understanding of the impact of transitions on ecosystem services is for 1st generation to 2nd generation dedicated bioenergy feedstocks. Here studies suggest significant benefits across a broad range of ecosystem services, although raise a question of whether transition of land currently used for food-crop production is desirable given the increased challenge of feeding a growing world population over the coming decades.

For the ecosystem services considered, conversion of forests to 2nd generation feedstock production will likely lead to a reduction in the provision of services, even when feedstocks with similar characteristics (such as SRC and SRF) are produced. Impacts will be associated with conversion from natural forest cover, although conversion from plantation forestry will likely reduce provision of services as well. A key driving mechanism behind this is the shortening of the management cycle, as the establishment and harvesting phase are associated with significant impacts. The use of existing plantations designed for harvesting and managed for productivity (Talbot & Ackerman, 2009), could make an important contribution to 2nd generation production, as could the adoption of best practice from the forestry sector (Lattimore *et al.*, 2009).

Production of 2nd generation bioenergy crops on marginal land seems to offer the best prospects for achieving sustainability. Although there are significant gaps in our understanding, such transitions would have the benefit of bringing currently under-utilized areas into production while either enhancing or having little impact on the provision of the services considered in this review. There is evidence that the value of marginal land for food production may be underestimated, particularly for the poorest sections of society. However, production could be targeted in areas where this conflict would not arise, or the bioenergy crop itself could represent an alternate source of income.

For iLUC, a tremendous amount of international work on different modelling approaches has been initiated since 2008, but as yet, these models are disparate, have different strengths and limitations and often work on inconsistent scenario approaches and underlying assumptions. It is questionable whether they provide adequate evidence for policy development, although on the basis of the precautionary approach, policy in the EU has now been forthcoming. Despite this, it seems likely that future work is required to bring modelling approaches together and to validate data where possible. This requires a multi-disciplinary approach and that should consider 2nd generation transitions in more detail than captured in the current modelling activities.

The last decade has seen the parallel emergence of policy designed to promote bioenergy as one route towards sustainable energy production, and an increasing understanding of the importance of ecosystem services for human health and wellbeing. Although our review highlights significant knowledge gaps, our understanding of 2nd generation bioenergy, their production potential and environmental impacts, is increasing. Similarly, there is growing understanding and a number of initiatives that have begun to map the provision of ecosystem services and human reliance upon them (Crossman *et al.,* Luck *et al.*, 2012). There is an opportunity to bring these groups together to formerly address the question of where the best and worst areas for 2nd generation bioenergy feedstock production are. Major questions to examine include: (1) what are the trade-off between bioenergy production and services? (2) where can bioenergy crops themselves provide or enhance services of value to humans? (3) will increased intensity of production affect relationships with service provision? Research should be a mix of both natural and social sciences and aim to build a holistic view of impacts on production areas across the range of ecosystem services. Ultimately, to inform policy direction and deployment of 2nd generation feedstocks, we would aim to understand where trade-offs arise between the provision of different services and production exist and what societal response to such trade-offs will be.

7. REFERENCES

Ajanovic A (2011) Biofuels versus food production: Does biofuels production increase food prices? *Energy,* **36**, 2070-2076.

Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. *Global Change Biology Bioenergy,* **1**, 75-96.

Arima EY, Richards P, Walker R, Caldas MM (2011) Statistical confirmation of indirect land use change in the Brazilian Amazon. *Environmental Research Letters,* **6**, 024010.

Aylott MJ, Casella E, Farrall K, Taylor G (2010) Estimating the supply of biomass from short-rotation coppice in England, given social, economic and environmental constraints to land availability. *Biofuels Bioproducts & Biorefining-Biofpr,* **5**, 719-727.

Aylott MJ, Casella E, Tubby I, Street NR, Smith P, Taylor G (2008) Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. *New Phytologist,* **178**, 358-370.

Balat M (2007) An overview of biofuels and policies in the European union. *Energy Sources Part B-Economics Planning and Policy,* **2**, 167-181.

Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Casella E, Taylor G (2010) Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. *Bioresource Technology,* **101**, 8132-8143.

Bessou C, Ferchaud F, Gabrielle B, Mary B (2011) Biofuels, greenhouse gases and climate change. A review. *Agronomy for Sustainable Development,* **31**, 1-79.

Bianchi FJJA, Booij CJH, Tscharntke T (2006) Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B-Biological Sciences,* **273**, 1715-1727.

Blanco-Canqui H (2010) Energy Crops and Their Implications on Soil and Environment. *Agronomy Journal,* **102**, 403-419.

Boardman J, Evans R (2006) Britain. In: *Soil Erosion in Europe* (eds Boardman J, Poesen J) Chichester, UK, John Wiley & Sons.

Bryan BA, Crossman ND, King D, Meyer WS (2011) Landscape futures analysis: Assessing the impacts of environmental targets under alternative spatial policy options and future scenarios. *Environmental Modelling & Software,* **26**, 83-91.

Busch G (2012) GIS-based Tools for Regional Assessments and Planning Processes Regarding Potential Environmental Effects of Poplar SRC. *Bioenergy Research,* **5**, 584-605.

Callesen I, Carter MS, Ostergard H (2011) Efficient use of reactive nitrogen for cultivation of bioenergy: less is more. *Global Change Biology Bioenergy,* **3**, 171-179.

Carvell C, Meek WR, Pywell RF, Goulson D, Nowakowski M (2007) Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *Journal of Applied Ecology,* **44**, 29-40.

Ceotto E (2008) Grasslands for bioenergy production. A review. *Agronomy for Sustainable Development,* **28**, 47-55.

Clarke D, Jablonski S, Moran B, Anandarajah G, Taylor G (2009) How can accelerated development of bioenergy contribute to the future UK energy mix? Insights from a MARKAL modelling exercise. *Biotechnology for Biofuels,* **2**, 1-19.

Committee on Climate Change (2011) Bioenergy Review. London, UK.

Crossman ND, Burkhard B, Nedkov S *et al.* A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*.

Dahms H, Mayr S, Birkhofer K, Chauvat M, Melnichnova E, Wolters V, Dauber J (2010) Contrasting diversity patterns of epigeic arthropods between grasslands of high and low agronomic potential. *Basic and Applied Ecology,* **11**, 6-14.

Dauber J, Jones MB, Stout JC (2010) The impact of biomass crop cultivation on temperate biodiversity. *Global Change Biology Bioenergy,* **2**, 289-309.

Department of Energy and Climate Change (2012) UK Bioenergy strategy. London, UK, DECC.

Dimitriou I, Mola-Yudego B, Aronsson P (2012) Impact of Willow Short Rotation Coppice on Water Quality. *Bioenergy Research,* **5**, 537-545.

Donnelly A, Styles D, Fitzgerald J, Finnan J (2011) A proposed framework for determining the environmental impact of replacing agricultural grassland with Miscanthus in Ireland. *Global Change Biology Bioenergy,* **3**, 247-263.

E4tech (2010) A causal descriptive approach to modelling the GHG emissions associated with the indirect land use change impacts of biofuels; final report prepared for UK Department for Transport; London.

EEA (2008) Maximising the environmental benefits of Europe's bioenergy potential; EEA Report No 10/2008; Copenhagen.

European Commission (2012) DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources In: *2012/0288 (COD)* (ed Commission E)

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science,* **319**, 1235-1238.

Felten D, Emmerling C (2011) Effects of bioenergy crop cultivation on earthworm communities - A comparative study of perennial (Miscanthus) and annual crops with consideration of graded land-use intensity. *Applied Soil Ecology,* **49**, 167-177.

Finch JW, Riche AB (2010) Interception losses from Miscanthus at a site in south-east England—an application of the Gash model. *Hydrological Processes,* **24**, 2594-2600.

Findlater KM, Kandlikar M (2011) Land use and second-generation biofuel feedstocks: The unconsidered impacts of Jatropha biodiesel in Rajasthan, India. *Energy Policy,* **39**, 3404-3413.

Fletcher RJ, Robertson BA, Evans J, Doran PJ, Alavalapati JRR, Schemske DW (2011) Biodiversity conservation in the era of biofuels: risks and opportunities. *Frontiers in Ecology and the Environment,* **9**, 161-168.

Foresight (2011) The Future of Food and Farming. Executive Summary. The Government Office for Science, London.

Fritsche UR, Wiegmann K, Oeko-Istitut (2011) Indirect land use change and biofuels, Environment , Public Health and Food Safety. Directorate General for Internal Policies, European Parliament.

Gallagher E (2008) The Gallagher Review of the indirect effects of biofuels production. Renewable Fuels Agency, East Sussex.

Gallai N, Salles J-M, Settele J, Vaissière BE (2009) Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics,* **68**, 810-821.

Gasparatos A, Stromberg P, Takeuchi K (2011) Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative. *Agriculture, Ecosystems & Environment,* **142**, 111-128.

Gawel E, Ludwig G (2011) The iLUC dilemma: How to deal with indirect land use changes when governing energy crops? *Land Use Policy,* **28**, 846-856.

GBEP (2011) Indirect effects of biofuel production. A report prepared by Ecofys.

Gonzalez-Garcia S, Mola-Yudego B, Dimitriou I, Aronsson P, Murphy R (2012) Environmental assessment of energy production based on long term commercial willow plantations in Sweden. *Science of the Total Environment,* **421**, 210-219.

Gopalakrishnan G, Negri MC, Salas W (2012) Modeling biogeochemical impacts of bioenergy buffers with perennial grasses for a row-crop field in Illinois. *Global Change Biology Bioenergy,* **4**, 739-750.

Gopalakrishnan G, Negri MC, Wang M, Wu M, Snyder SW, Lafreniere L (2009) Biofuels, Land, and Water: A Systems Approach to Sustainability. *Environmental Science & Technology,* **43**, 6094-6100.

Haney RL, Kiniry JR, Johnson MVV (2010) Soil microbial activity under different grass species: Underground impacts of biofuel cropping. *Agriculture Ecosystems & Environment,* **139**, 754-758.

Hardcastle PD (2006) A review of the potential impacts of short rotation forestry. LTS International, http://www.forestry.gov.uk/pdf/SRFFinalreport27Feb.pdf/$FILE/SRFFinalreport27Feb.pdf.

Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of miscanthus. *Global Change Biology,* **14**, 2000–2014.

Hickman GC, Vanloocke A, Dohleman FG, Bernacchi CJ (2010) A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. *Global Change Biology Bioenergy,* **2**, 157-168.

Hiederer R, Ramos F, Capitani C *et al.* (2010) Biofuels: a new methodology to estimate GHG emissions from global land use change. *JRC Scientific and Technical Reports, EUR,* **24483**.

Holzschuh A, Steffan-Dewenter I, Kleijn D, Tscharntke T (2007) Diversity of flower-visiting bees in cereal fields: effects of farming system, landscape composition and regional context. *Journal of Applied Ecology,* **44**, 41-49.

Iea (2010) Bioenergy 2010: Bioenergy, Land Use Change and Climate Change Mitigation - Report for Policy Advisors and Policy Makers; Berndes,Göran/Bird, Neil/Cowie, Annette; ExCo:2010:03.

Klein AM, Vaissiere BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C, Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. *Proc Biol Sci,* **274**, 303-313.

Kocoloski M, Michael Griffin W, Scott Matthews H (2011) Impacts of facility size and location decisions on ethanol production cost. *Energy Policy,* **39**, 47-56.

Kremen C, Williams NM, Aizen MA *et al.* (2007) Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. . *Ecology Letters,* **10**, 299-314.

Landis DA, Gardiner MM, Van Der Werf W, Swinton SM (2008) Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. *Proceedings of the National Academy of Sciences of the United States of America,* **105**, 20552-20557.

Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G (2009) Environmental factors in woodfuel production: Opportunities, risks, and criteria and indicators for sustainable practices. *Biomass & Bioenergy,* **33**, 1321-1342.

Le PVV, Kumar P, Drewry DT (2011) Implications for the hydrologic cycle under climate change due to the expansion of bioenergy crops in the Midwestern United States. *Proceedings of the National Academy of Sciences of the United States of America,* **108**, 15085-15090.

Love BJ, Einheuser MD, Nejadhashemi AP (2011) Effects on aquatic and human health due to large scale bioenergy crop expansion. *Science of the Total Environment,* **409**, 3215-3229.

Lovett AA, Sunnenberg GM, Richter GM, Dailey AG, Riche AB, Karp A (2009) Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for Miscanthus in England. *Bioenergy Research,* **2**, 17-28.

Luck GW, Chan KM, Klien CJ (2012) Identifying spatial priorities for protecting ecosystem services. *F1000Research,* **1**.

Mcbride AC, Dale VH, Baskaran LM *et al.* (2011) Indicators to support environmental sustainability of bioenergy systems. *Ecological Indicators,* **11**, 1277-1289.

Meehan TD, Hurlbert AH, Gratton C (2010) Bird communities in future bioenergy landscapes of the Upper Midwest. *Proceedings of the National Academy of Sciences of the United States of America,* **107**, 18533-18538.

Meehan TD, Werling BP, Landis DA, Gratton C (2011) Agricultural landscape simplification and insecticide use in the Midwestern United States. *Proceedings of the National Academy of Sciences of the United States of America,* **108**, 11500-11505.

Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being: Synthesis. . Island Press, Washington, DC.

Naik SN, Goud VV, Rout PK, Dalai AK (2010) Production of first and second generation biofuels: A comprehensive review. *Renewable and Sustainable Energy Reviews,* **14**, 578-597.

Naylor RL, Liska AJ, Burke MB, Falcon WP, Gaskell JC, Rozelle SD, Cassman KG (2007) The ripple effect: Biofuels, food security, and the environment. *Environment,* **49**, 30-43.

Ng TL, Eheart JW, Cai XM, Miguez F (2010) Modeling Miscanthus in the Soil and Water Assessment Tool (SWAT) to Simulate Its Water Quality Effects As a Bioenergy Crop. *Environmental Science & Technology,* **44**, 7138-7144.

Nigam PS, Singh A (2011) Production of liquid biofuels from renewable resources. *Progress in Energy and Combustion Science,* **37**, 52-68.

Novo A, Jansen K, Slingerland M, Giller K (2010) Biofuel, dairy production and beef in Brazil: competing claims on land use in Sao Paulo state. *Journal of Peasant Studies,* **37**, 769-792.

OECD (2009) JRC/EEA/OECD Expert Consultation on "Review and inter-comparison of modelling land use change effects of bioenergy", OECD Conference Centre, Paris, 29-30 January 2009.

OEKO (2010) The "iLUC Factor" as a Means to Hedge Risks of GHG Emissions from Indirect Land Use Change Associated with Bioenergy Feedstock Production; Fritsche, Uwe R./Hennenberg, Klaus/Hünecke, Katja; prepared for BMU; Darmstadt

Oliver RJ, Finch JW, Taylor G (2009) Second generation bioenergy crops and climate change: a review of the effects of elevated atmospheric CO2 and drought on water use and the implications for yield. *Global Change Biology Bioenergy,* **1**, 97-114.

Pardue SL (2010) Food, energy, and the environment. *Poultry Science,* **89**, 797-802.

Pbl (2010) Identifying the indirect effects of bio-energy production; Bilthoven.

Pellegrino E, Di Bene C, Tozzini C, Bonari E (2011) Impact on soil quality of a 10-year-old short-rotation coppice poplar stand compared with intensive agricultural and uncultivated systems in a Mediterranean area. *Agriculture Ecosystems & Environment,* **140**, 245-254.

Plevin RJ, O'hare M, Jones AD, Torn MS, Gibbs HK (2010) Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environmental Science & Technology,* **44**, 8015-8021.

Potts SG, Woodcock BA, Roberts SPM, Tscheulin T, Pilgrim ES, Brown VK, Tallowin JR (2009) Enhancing pollinator biodiversity in intensive grasslands. *Journal of Applied Ecology,* **46**, 369-379.

Power AG (2010) Ecosystem services and agriculture: tradeoffs and synergies. *Philosophical Transactions of the Royal Society B-Biological Sciences,* **365**, 2959-2971.

Qin ZC, Zhuang QL, Chen M (2012) Impacts of land use change due to biofuel crops on carbon balance, bioenergy production, and agricultural yield, in the conterminous United States. *Global Change Biology Bioenergy,* **4**, 277-288.

Raunikar R, Buongiorno J, Turner JA, Zhu SS (2010) Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. *Forest Policy and Economics,* **12**, 48-56.

Richter GM, Riche AB, Dailey AG, Gezan SA, Powlson DS (2008) Is UK biofuel supply from Miscanthus water-limited? *Soil Use and Management,* **24**, 235-245.

Riffell S, Verschuyl J, Miller D, Wigley TB (2011) A meta-analysis of bird and mammal response to short-rotation woody crops. *Global Change Biology Bioenergy,* **3**, 313-321.

Robertson BA, Doran PJ, Loomis ER, Robertson JR, Schemske DW (2011a) Avian Use of Perennial Biomass Feedstocks as Post-Breeding and Migratory Stopover Habitat. *Plos One,* **6**.

Robertson BA, Doran PJ, Loomis ER, Robertson JR, Schemske DW (2011b) Avian Use of Perennial Biomass Feedstocks as Post-Breeding and Migratory Stopover Habitat. *Plos One,* **e16941**.

Robertson BA, Doran PJ, Loomis LR, Robertson JR, Schemske DW (2011c) Perennial biomass feedstocks enhance avian diversity. *Global Change Biology Bioenergy,* **3**, 235-246.

Rowe RL, Hanley ME, Goulson D, Clarke DJ, Doncaster CP, Taylor G (2011) Potential benefits of commercial willow Short Rotation Coppice (SRC) for farm-scale plant and invertebrate communities in the agri-environment. *Biomass & Bioenergy,* **35**, 325-336.

Rowe RL, Street NR, Taylor G (2009) Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. *Renewable & Sustainable Energy Reviews,* **13**, 271-290.

Sanderson MA, Adler PR (2008) Perennial forages as second generation bioenergy crops. *International Journal of Molecular Sciences,* **9**, 768-788.

Schleupner C, Link PM (2008) Potential impacts on important bird habitats in Eiderstedt (Schleswig-Holstein) caused by agricultural land use changes. *Applied Geography,* **28**, 237-247.

Schulze ED, Korner CI, Law BE, Haberl H, Luyssaert S (2012) Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *Global Change Biology Bioenergy,* **4**, 611-616.

Searchinger T, Heimlich R, Houghton RA *et al.* (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science,* **319**, 1238-1240.

Sharman A, Holmes J (2010) Evidence-Based Policy or Policy-Based Evidence Gathering? Biofuels, the EU and the 10% Target. *Environmental Policy and Governance,* **20**, 309-321.

Smith KA, Searchinger TD (2012) Crop-based biofuels and associated environmental concerns. *Global Change Biology Bioenergy,* **4**, 479-484.

Smith P, Ashmore M, Black H *et al.* (2011) Regulating Services. . In: *The UK National Ecosystem Assessment Technical Report. .* UK National Ecosystem Assessment, UNEP-WCMC, Cambridge.

Smith P, Davies CA, Ogle S *et al.* (2012) Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology,* **18**, 2089-2101.

Steffan-Dewenter I, Westphal C (2008) The interplay of pollinator diversity, pollination services and landscape change. *Journal of Applied Ecology,* **45**, 737-741.

Stone KC, Hunt PG, Cantrell KB, Ro KS (2010) The potential impacts of biomass feedstock production on water resource availability. *Bioresource Technology,* **101**, 2014-2025.

Syswerda SP, Basso B, Hamilton SK, Tausig JB, Robertson GP (2012) Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. *Agriculture Ecosystems & Environment,* **149**, 10-19.

Talbot B, Ackerman PA (2009) Renewable energy: the potential opportunities and obligations of plantation forestry. *Southern Forests,* **71**, 79-83.

The Royal Society (2008) Sustainable biofuels: prospects and challenges. London, UK, The Royal Society, .

Thomson LJ, Hoffmann AA (2011) Pest management challenges for biofuel crop production. *Current Opinion in Environmental Sustainability,* **3**, 95-99.

Tilman D, Socolow R, Foley JA *et al.* (2009) Beneficial Biofuels-The Food, Energy, and Environment Trilemma. *Science,* **325**, 270-271.

Tirado MC, Cohen MJ, Aberman N, Meerman J, Thompson B (2010) Addressing the challenges of climate change and biofuel production for food and nutrition security. *Food Research International,* **43**, 1729-1744.

U.S. Energy Information Administration (2013) International Energy Statistics.

UK National Ecosystem Assessment (2011) The UK National Ecosystem Assessment Technical Report. UNEP-WCMC, Cambridge.

UNEP (United Nations Environment Programme)/Rsb (Roundtable on Sustainable Biofuels)/Ipieaca (International Petroleum Industry Environmental Conservation Association) (2009) Indirect Land-Use Change: A stakeholder debate on the science and policy impacts of sustainable biofuel production; Workshop Nov. 9-10, 2009, Lausanne.

Updegraff K, Baughman MJ, Taff SJ (2004) Environmental benefits of cropland conversion to hybrid poplar: economic and policy considerations. *Biomass & Bioenergy,* **27**, 411-428.

US EPA (2010) Renewable Fuel Standard (RFS2): Program Amendments; Washington DC.

Vaknin Y (2011) The Significance of Pollination Services for Biodiesel Feedstocks, with Special Reference to Jatropha curcas L.: A Review. *Bioenergy Research,* **5**, 32-40.

Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P (2012) Food vs. fuel: the use of land for lignocellulosic next generation' energy crops that minimize competition with primary food production. *Global Change Biology Bioenergy,* **4**, 1-19.

Van Der Horst D, Vermeylen S (2011) Spatial scale and social impacts of biofuel production. *Biomass and Bioenergy,* **35**, 2435-2443.

Vanloocke A, Bernacchi CJ, Twine TE (2010) The impacts of Miscanthus x giganteus production on the Midwest US hydrologic cycle. *Global Change Biology Bioenergy,* **2**, 180-191.

Vanloocke A, Twine TE, Zeri M, Bernacchi CJ (2012) A regional comparison of water use efficiency for miscanthus, switchgrass and maize. *Agricultural and Forest Meteorology,* **164**, 82-95.

Werling BP, Meehan TD, Robertson BA, Gratton C, Landis DA (2011) Biocontrol potential varies with changes in biofuel-crop plant communities and landscape perenniality. *Global Change Biology Bioenergy,* **3**, 347-359.

Whitaker J, Ludley KE, Rowe R, Taylor G, Howard, DC (2010) Sources of variability in greenhouse gas and energy balances for biofuel production: a systematic review. Global Change Biology Bioenergy, **2(3)**, 99-112

Wilson HM, Cruse RM, Burras CL (2011) Perennial grass management impacts on runoff and sediment export from vegetated channels in pulse flow runoff events. *Biomass & Bioenergy,* **35**, 429-436.

Wu YP, Liu SG (2012) Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin. *Biomass & Bioenergy,* **36**, 182-191.

Yang H, Zhou Y, Liu JG (2009) Land and water requirements of biofuel and implications for food supply and the environment in China. *Energy Policy,* **37**, 1876-1885.

Zona D, Janssens I, Aubinet M, Gioli B, Vicca S, Fichot R, Ceulemans R (2013) Fluxes of the greenhouse gases (CO2, CH4 and N2O) above a short-rotation poplar plantation after conversion from agricultural land. *Agricultural and Forest Meteorology,* **169**, 100-110.