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Land use implications of future energy system trajectories—The case of the UK 2050 Carbon Plan

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HIGHLIGHTS

- The Carbon Plan could result in significant land use change for bioenergy by 2050.
- Higher Nuclear; less efficiency pathway has the highest land use change impact.
- Higher Renewables; more energy efficiency pathway has the lowest land use change impact.
- Transport decarbonisation via biofuels has the highest land use change impacts.
- At current deployment rate only Higher Renewables pathway projections is achievable.

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ABSTRACT

The UK's 2008 Climate Change Act sets a legally binding target for reducing territorial greenhouse gas emissions by 80% by 2050, relative to 1990 levels. Four pathways to achieve this target have been developed by the Department of Energy and Climate Change, with all pathways requiring increased us of bioenergy. A significant amount of this could be indigenously sourced from crops, but will increased domestic production of energy crops conflict with other agricultural priorities?

To address this question, a coupled analysis of the UK energy system and land use has been developed. The two systems are connected by the production of bioenergy, and are projected forwards in time under the energy pathways, accounting for various constraints on land use for agriculture and ecosystem services.

The results show different combinations of crop yield and compositions for the pathways lead to the appropriation of between 7% and 61% of UK's agricultural land for bioenergy production. This could result in competition for land for food production and other land uses, as well as indirect land use change in other countries due to an increase in bioenergy imports. Consequently, the potential role of bioenergy in achieving UK emissions reduction targets may face significant deployment challenges.

1. Introduction

The deployment of low-carbon/renewable energy, in particular bioenergy, as substitutes for fossil fuel in transport and heat delivery has been shown to have the potential of playing a significant role in the future UK energy systems (Jablonski et al., 2010). The UK Department of Energy and Climate Change (DECC) in its pursuit of ensuring a low-carbon energy future, has developed the 2050 Carbon Plan (HM Government, 2011). The Carbon Plan is made up of four low-carbon energy system pathways that achieve the 80% greenhouse gas (GHG) emissions cut target of the Climate Change Act (2008) (HM Government, 2008) by 2050. These are: "Core MARKAL"; "Higher Renewables, more energy efficiency"; "Higher Nuclear, less energy efficiency"; and "Higher Carbon Capture and Storage (CCS), more bioenergy". The energy and technology mix of all these pathways have a significant composition of renewables. With the exception of hydro, tidal and offshore wind power generation, the majority of renewable energy systems involve some form of land use – bioenergy being the most land intensive. Thus, a fundamental question for policy is whether these pathways could have a significant impact on land use, and if so, could this create competition between energy, food and other land services for available suitable UK land? Answering this

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question requires a comprehensive analysis of the land required under each of the pathways and for other land services, vis-à-vis the available UK land. This is the main objective of the current study.

The Carbon Plan assumes that a range of bioenergy sources can assist with the achievement of the bioenergy projections for each of its pathways, including bioenergy from crops, dedicated and waste wood fuel, agricultural residue, and biomass waste in landfill. These provide the raw materials for the generation of electricity, heat and liquid biofuels. Potential land use impact in this context would therefore be mainly associated with the production of energy crops. Currently, bioenergy feedstock for heat and electricity generation is mainly from imported solid biomass, with a limited supply of wastes and straw sourced indigenously (AEA, 2014). Additionally, 85% of crop-based feedstock for biofuels for road transport for 2013/14 in the UK was imported (DEFRA, 2014a, 2014b). While the Carbon Plan envisages the importation of a greater portion of UK bioenergy feedstock to continue in the future, there is scope for a significant amount to be indigenously sourced, including bioenergy from energy crops. It is therefore important to assess requirements for land to produce the anticipated increase in indigenous bioenergy, and to explore whether restrictions on land availability could prevent realisation of future energy system targets.

According to the UK's Department for Environment, Food and Rural Affairs (DEFRA), 51,000 ha (0.8%) of UK arable land was used for the production of bioenergy in the UK in 2014 (DEFRA, 2014a, 2014b). Out of this land area, 42,000 ha was for the production of first-generation energy crops (including wheat, oil seed rape, and sugar beets) used in the production of liquid transport biofuels (biodiesel and bioethanol). The remainder (9000 ha) was used in the production of second-generation energy crops, mainly short rotation coppice (SRC) and Miscanthus, which is used for heat and electricity generation. This level of land appropriation for bioenergy production threaten other uses. However, future changes in the UK energy system, could according to Popp et al. (2014), result in significant changes to the current UK agricultural landscape and management practices. This might include sustainable intensification that improves yields, with increased fertilizer application, and replacement of certain crops (e.g. Franks, 2014; Fish et al., 2014), or by exploitation of unused arable land, as well as use of other productive and marginal lands (e.g. Horrocks et al., 2014). This increased indigenous feedstock production could lead to some level of future land stress in the UK. Additionally analysis by Smith et al. (2010) of UK land use and food production suggests that with future increases in population and food demand, increased competition for suitable land for bioenergy supply, food production and other land services could arise. Moreover, the EU Renewable Energy Directive, sets out binding sustainability criteria for sourcing bioenergy, stipulating that feedstock are sourced without loss of high carbon lands including forests, peat and bog, that biodiversity is maintained, and that protected areas including conservation, national parks and primary vegetation cover are preserved (EU, 2009).

Currently, there are no specific policy targets for UK-sourced crop-based bioenergy, and by extension there are no targets for areas of land that would be required. However, several government publications have estimates land requirements. According to the UK Bioenergy strategy (DECC, 2012a, 2012b) between 300,000 ha and 900,000 ha of UK agricultural land could be required by 2030. Analysis in the 2011 Bioenergy Review of the Committee on Climate Change (CCC) envisages that between 300,000 ha and 800,000 ha would be required by 2050 to deliver between 15 TW h and 70 TW h energy (CCC, 2011). Prior to these reports, DEFRA's 2007 UK Biomass Strategy also projected that up to 350,000 ha and 800,000 ha would be required by 2020 and 2050 respectively. Studies on the availability of land for bioenergy production in the UK have a range of outcomes, particularly for second-generation energy crops, which are projected to be the main future bioenergy feedstock (HM Government, 2011). Considering various limiting factors, including physical limits to production (topography, drainage etc.), biodiversity conservation, socio-cultural services, existing land use, and a variety of landscape designations and aesthetics, Lovett et al. (2014) estimated that about 8.5 Mha ~37% of the UK's agricultural land, is potentially suitable for perennial bioenergy production. According to a report by Ricardo-AEA (2014) for DEFRA, this potential suitable land decreases to 6.4 Mha if Agricultural Land Class (ALC) Grades 1 and 2 land were excluded, and decreases further to 1.4 Mha if ALC Grade 3 land was also excluded. There is however, a wide range of estimates of available land that could be converted to bioenergy production due to differences in the assumptions used. According to Welfle et al. (2014), if food security, economic development, conservation, and bioenergy were prioritised for land use to 2050, between 0.7 and 2.2 Mha could be available. Aylott and McDermott (2012) also concluded that between 0.93 and 3.63 Mha of land for Miscanthus and SRC production in the UK could be available. However, if a gross margin of £526/ha for Miscanthus (at £60/odt) is assumed to be the minimum acceptable to farmers, the maximum available area reduces to 0.72–2.80 Mha. Similarly, at a gross minimum margin of £241/ha for SRC (at £60/odt) the land availability decreases to 0.62–2.43 Mha (Aylott and McDermott, 2012).

Other studies have also looked at the wider ecosystem and biodiversity impacts of large-scale bioenergy deployment in the UK. The studies have shown that second-generation energy crops (such SRC and Miscanthus), will probably have positive effects on soil properties, biodiversity, energy balance, greenhouse gas (GHG) mitigation, carbon footprint and visual impact when compared to arable crops (e.g. Rowe et al., 2009; Thornley et al., 2009; Rowe et al., 2013; Milner et al., in press; Holland et al., 2015). However, the positive effects depend mainly on previous land uses rather than the choice of the second-generation crop, with a transition from arable crops to bioenergy being best (Milner et al., in press). Additionally, if not managed carefully, bioenergy production could pose a significant challenge to maintaining biodiversity and the ecosystem services currently provided by land (Rowe et al., 2009)

Whilst most of these analyses are predicated on UK and/or EU policy, none have directly analysed the land implications of the energy pathways in the Carbon Plan. This study therefore aims to analyse the land use requirements of the four Carbon Plan pathways from 2010 to 2050 under different scenarios of yield and energy crop composition and considers the implication of these pathways on other land services including food production, settlement expansion and biodiversity protection.

2. Methodology

To determine how the UK Carbon Plan pathways could lead to competition for agricultural land, this study uses a top-down analysis of the interconnections between the land and energy systems, followed by the estimation of the area of land required to deliver the bioenergy component the pathways, and how this affects UK land use distribution. First, linkages between the energy and land systems were mapped out and the current land area appropriated for energy crops was analysed. Next, the land area requirements for the projected bioenergy component of each pathway, and for other services were estimated. Then the, land use distribution under each pathway was analysed using criteria that prioritise food production and the maintenance of ecosystem services to establish potential land stress and competition

between different services. Finally, the rate of land appropriation for bioenergy crops under each pathway was compared to current rates of deployment. Details of the data sources and the analysis are presented in the following sub-sections.

2.1. Land and energy system linkages

To link the energy and land systems and identify those interconnections from the energy system with the highest potential to cause land use change, the whole UK energy system was disaggregated into the various stages that transform primary energy resources into energy vectors that fulfil the demand of the final sectors, in the form of a Sankey diagram. The main links between the energy system and the land system analysed in this work occur via the transformation of the final bioenergy vectors into electricity and heat, and direct consumption of final bioenergy vectors in various sectors (transport, industry, domestic and commercial buildings, and agriculture). The intermediate flow of energy through conversion devices and passive systems was also characterised, based on the approach used by Cullen and Allwood (2010) and Ma et al. (2012) to study global and Chinese energy systems, respectively. This type of diagram has been previously used by Hammond and Stapleton (2001) to describe the energy system of the UK, in the annual Digest of UK Energy Statistics (DUKES) publication by DECC since 2010 and the DECC Calculator tool (DECC, 2014a).

The Carbon Plan pathways present different options for the integration of bioenergy into the future energy system, as shown in Fig. 1 (and SI Table 1). All pathways project a significant increase in bioenergy deployment, ranging from 18% to 42% of total primary energy demand. As shown in Fig. 1a, the pathways have different overall primary bioenergy resource levels, with waste, imported resources and dedicated crops all forming part of the bioenergy mix. The allocation of these bioenergy resources to transformation and end-use sectors is significantly different for all the pathways (Fig. 1b). A detailed description of the data sources used for the Sankey diagrams, and the configurations of the Carbon Plan pathways associated with land use are provided in Appendix A.

Analysis of land system linkages to the energy system begins with estimation of the area of land committed to bioenergy cropping, published in DECC and DEFRA statistics for the base year (2010); followed by estimation of future land requirements for bioenergy cropping for different land use and crop yield scenarios. In addition to the land required for indigenous bioenergy, the

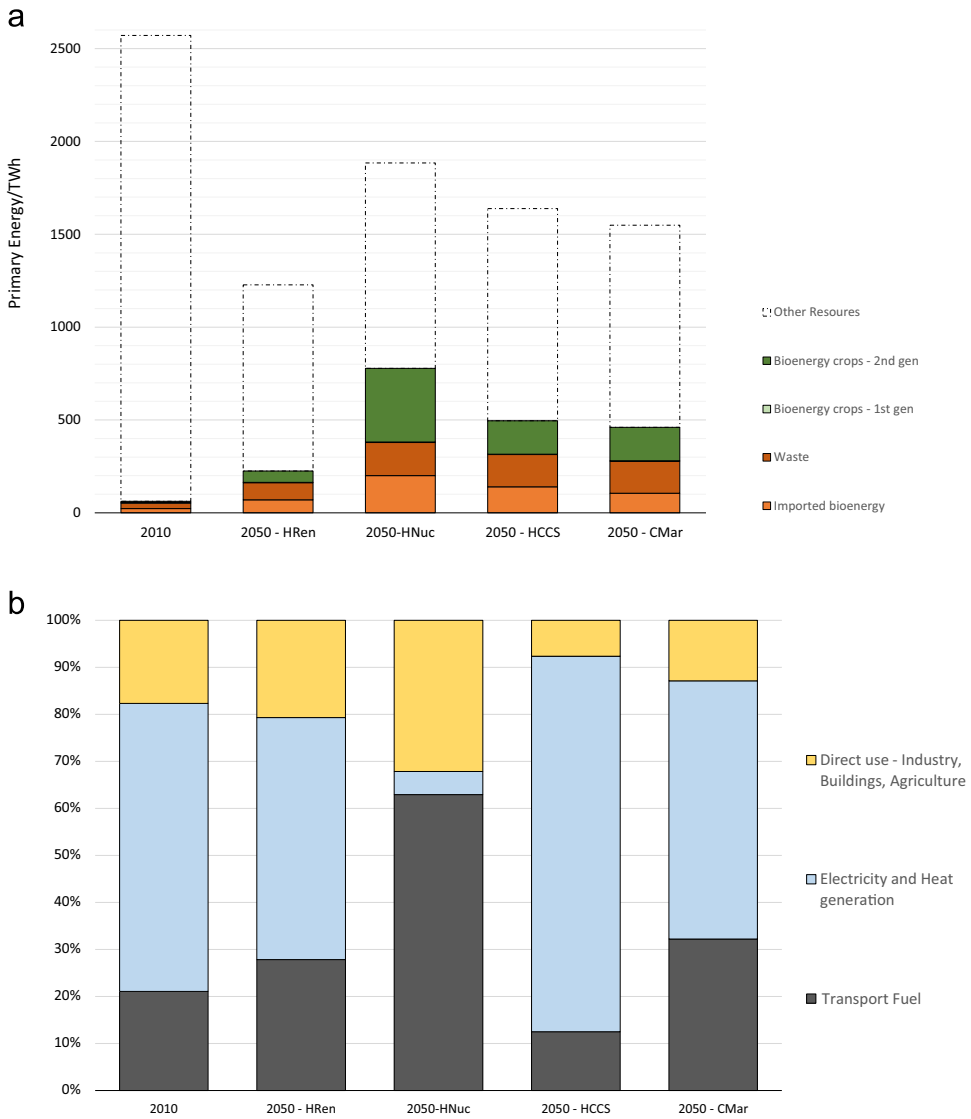

Fig. 1. UK primary bioenergy mix: (a) and downstream options for final bioenergy vectors; (b) the four Carbon Plan pathways in 2010 and 2050 – bioenergy options for different pathways (with HRen – "Higher Renewables, more energy efficiency", HNuc – "Higher Nuclear, less energy efficiency", HCCS – "Higher CCS, more bioenergy", "CMar" – Core MARKAL). (b) Downstream options for bioenergy.

Table 1
Data sources.

Data type	Source
UK Bioenergy projection to 2050	DECC (2012a, 2012b)
Land cover (including natural and semi-natural habitats)	Centre for Ecology & Hydrology (2010)
Agriculture Land Classification (England & Wales)	DEFRA (Formerly MAFF) (1988), Welsh Government (2010)
Land Suitability for Agriculture (Scotland)	Soil Survey of Scotland Staff (1981)
UK Agricultural statistics (including bioenergy cropping)	DEFRA (2013)
Environmental Designation (e.g. nature reserves, SSSI, Conservation)	DEFRA
National Parks	DEFRA (accessed 2014)
Carbon Plan Pathways (data on primary sources, transformation, conversion devices and final energy use by sector)	DECC Calculator version 3.4.1
Onshore/Offshore natural gas and oil wells	DECC data for oil and gas
Energy system	Digest of UK Energy Statistics (DUKES) 2011 and 2013 (DECC, 2012a, 2014b)
Additional energy demand data	Energy Consumption in the UK (ECUK), DECC (accessed 2014) Direct energy use in agriculture (Warwick and Park, 2007 for DEFRA)

"avoided land" associated with imported bioenergy and food was also estimated. The land system was disaggregated into four categories: suitability for agriculture; environmental designation; aggregated land cover types based on broad habitats; actual land use types. This disaggregation provided the basis, for estimating the availability of different land use types, their suitability for agriculture, and the availability of land for other services. A summary of the data types and sources used in this study is presented in Table 1 (detailed description in Appendix A).

2.2. Estimation of land requirements for the Carbon Plan pathways

Future land use for bioenergy was estimated for different scenarios of yield and crop composition. Two yield scenarios were considered; a Progress-As-Usual (PAU) yield scenario and an improved yield scenario. The PAU yield scenario assumes no significant change in crop yields. The improved yield scenario is based on DECC's projection for increases in energy crop yield by 30% on current yields by 2050 (DECC, 2014a, 2014b). Two scenarios of crop composition were also considered: Progress-As-Usual (PAU) and "50/50" scenarios. The PAU scenario assumes the same crop composition as the base year (2010), while the "50–50" scenario assumes a future bioenergy crop composition of 50% each for both first-generation (wheat and sugar beets) and second-generation (Miscanthus and SRC) crops.

Land area requirements were estimated the energy density (heating value) factors of each crop, and projected crop yields. The energy density factors were based on the US Department of Energy (US DOE) heat content ranges for various biomass fuels (US DOE/ORNL, 2011) (SI Table 2). Projections for future demand for non-energy (food and fibre) crops were based on the assumption that both diet composition and food imports would be as at present. Thus, the area of land required for indigenously-produced food was estimated using UK population projections (ONS, 2014), projected crop yields and the current per capita demand for indigenously-produced crops.

The "avoided land", the extra demand for land in the UK if all imported food, fibre and bioenergy that could be indigenously produced was in fact produced in the UK, was also estimated for both imported bioenergy and food. Future demand for settlement and forest/woodland expansion are projected to increase annually by 15 kha and 17 kha, respectively, for all pathways (HM Government, 2010). To analyse progress of the land appropriation for bioenergy in the UK, the rate of land use change to bioenergy crops between 2011 and 2013 was extrapolated to 2030, using published DEFRA statistics (DEFRA, 2014b). These trends of land appropriation were then compared the projected land requirements under the Carbon Plan pathways to test whether these projection are attainable under the historical rates of deployment. Additionally, the estimated land requirements were also compared with the Bioenergy Strategy 2030 estimation of sustainable land use change to bioenergy crops.

2.3. Analysis of future land use distribution under the Carbon Plan pathways

In order to assess the impact of future demand for bioenergy on UK land use distribution, we projected the overall land areas required by different land services to 2050 using allocation criteria that prioritise food production and maintenance of ecosystem services. The allocation of land for future use was based on hierarchical priority criteria of "biodiversity protection and food production, before low-carbon energy/GHG sequestration". This is consistent with both EU sustainable bioenergy sourcing criteria (EU, 2009) and the need for food security. Land earmarked for biodiversity conservation and ecosystem protection was accordingly ring-fenced. Following Lovett et al. (2014), National Parks, Sites of Special Scientific Interests (SSSI), nature conservation and protected sites were excluded. Areas of high soil carbon composition such as peatlands were also excluded. Allocation of land for projected food production was prioritised over bioenergy production, and arable land given top priority. Unused arable land was then allocated to bioenergy production. Allocation for projected forestry and settlement changes was made from improved grassland. If the available unused arable land was insufficient for projected bioenergy needs, improved grassland was allocated for conversion to bioenergy production. In an extreme situation of land stress, semi-natural grassland, which usually has high biodiversity (Wilson et al., 2012), was allocated for bioenergy production.

3. Results

The results of this study show that the land requirements to meet bioenergy demand under the Carbon Plan pathways could lead to significant land use change impacts, and could result in increased competition for suitable agricultural land in the UK. The results presented in this section also show that the land area requirements significantly exceed the UK Bioenergy Strategy's 2030 estimation of sustainable land-use for most pathways. The level of land stress, however, varies (Fig. 4). At current rates of deployment, yields and composition, the projected rate of land appropriation required by the pathways is likely to be missed, both in the short-to-medium term (up to 2030) and by 2050. A detailed description of the results is presented in the next subsections, starting with the main connections between the energy and land use systems. This is followed by the land requirements and future

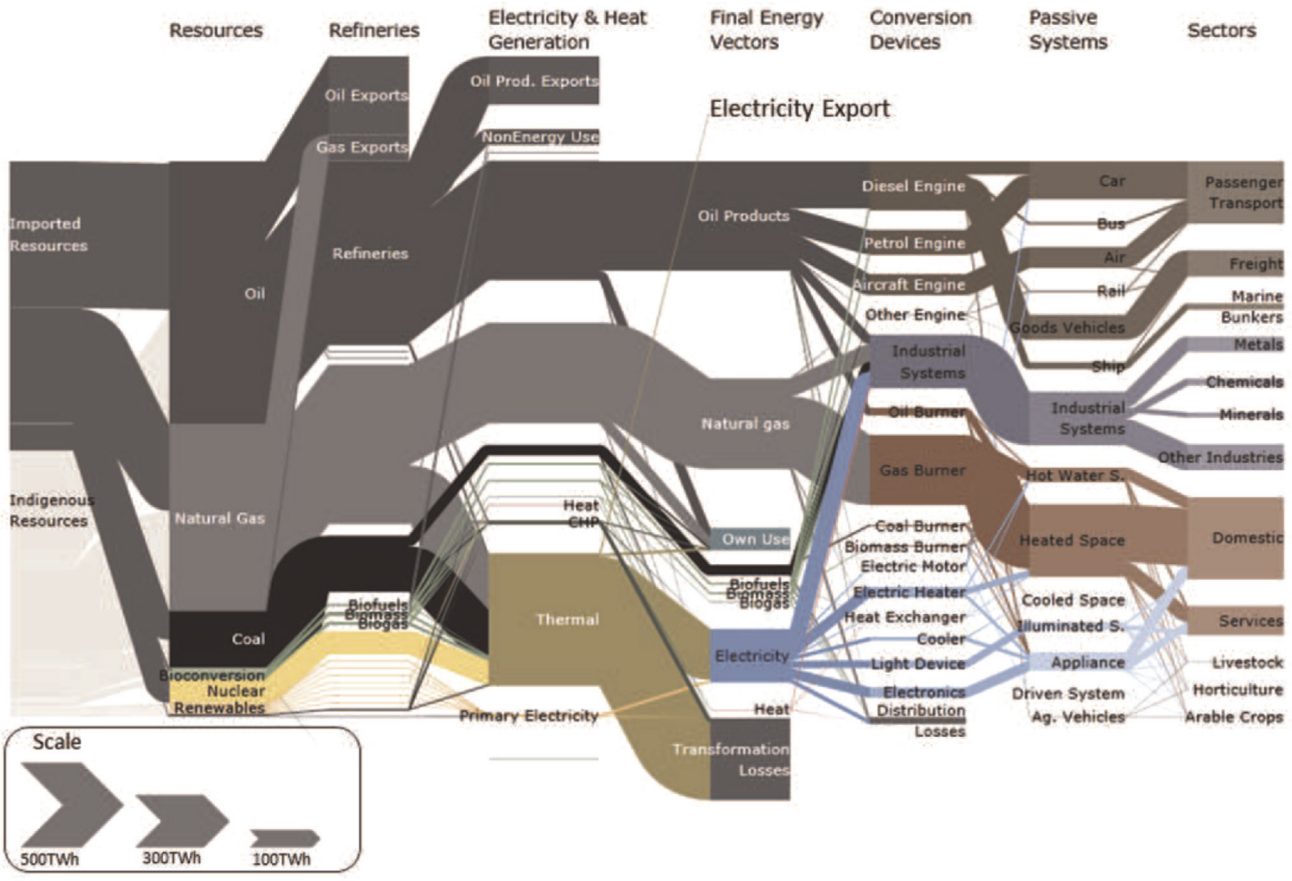

Fig. 2. Disaggregated UK energy system (2010).

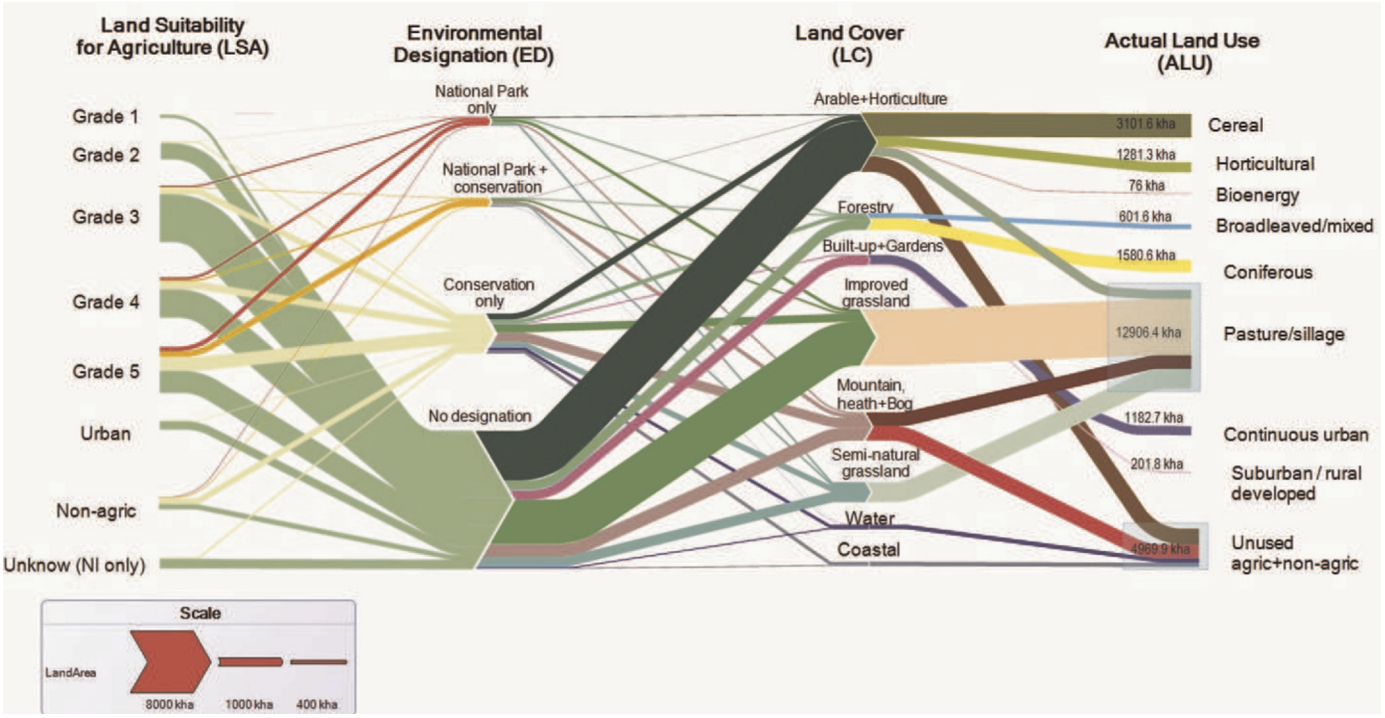

Fig. 3. Disaggregated UK land use system (2010).

land use distribution under the Carbon Plan pathways. The last subsection then presents the land appropriation for bioenergy under each pathway and how these compare with 2030 UK Bioenergy Strategy's estimation of sustainable land use.

3.1. Current UK energy and land use systems connections

Fig. 2 presents a Sankey diagram for the base year (2010) UK energy system, showing the flow of energy from primary resources to final use sectors. The main connections to the UK land system occur upstream (the supply side of the diagram) via primary bioenergy specifically that sourced from indigenous energy crops. However, the overall primary resource mix is predicated on downstream options in the energy system, such as the relative share of transport fuels, electricity and heat sourced from bioenergy.

Fig. 3 presents the UK land use system for the base year (2010) also as a Sankey diagram, identifying the agricultural land suitability classes and the environmental designations, and the land covers and land uses associated with these. The direct connection between the energy and land systems is at the level of the actual land use, where the area of land used in bioenergy cropping is assessed.

3.2. Future UK land requirement for energy under the Carbon Plan pathways

Table 2 presents the projected percentage of UK land required for bioenergy production by 2050 for each of the Carbon Plan pathways under the different scenarios of energy crop composition and yield change. The "Higher Nuclear, less energy efficiency" and "Higher Renewables, more energy efficiency" energy pathways present the highest and lowest land use impact respectively, across all the scenarios of yield and energy crop composition. The projected agricultural land appropriation for indigenous bioenergy production under the Higher Nuclear pathway ranges between 5.5 Mha and 10.6 Mha by 2050; representing between 26% and 61% of the UK's agricultural land area. By contrast, the projected land area required for indigenous bioenergy cropping by 2050 under the "Higher Renewable" pathway is between 1.2 Mha and 1.7 Mha, representing between 7% and 10% of UK agricultural land area. The results also show "Core MARKAL" and "High CCS" pathways have the same projected land requirements by 2050 (because of the similarity of the projected bioenergy composition of these two pathways). The overall impact of these changes in the land required for bioenergy on the future land use distribution in the UK is presented in the next section.

The projected "avoided land" for energy follows a similar pattern to the projected indigenous land appropriation, with the highest and lowest projected avoided land use impact associated with the "Higher Nuclear, less energy efficiency" and "Higher Renewables, more energy efficiency" pathways, respectively (4.1 Mha for "Higher Nuclear, less energy efficiency" and 1.7 Mha for "Higher Renewables, more energy efficiency", or 19% and 8% of UK land that will be externally sourced to meet the projected energy demand under these pathways). The "avoided land" associated with both energy and food imports by 2050 is presented in SI Table 3, for all pathways. Scenario results for all combinations of crop composition and yield can be accessed via the online UK Foreseer tool (Allwood et al., 2014)

Table 2
Projected area of land required for bioenergy as a percentage of UK agricultural land to under different crop composition and yield scenarios for each of the Carbon Plan pathways.

Scenarios		Projected percentage of UK Agricultural land required for bioenergy by 2050			
Yield	Crop composition	Core MARKAL (%)	Higher Renewable (%)	Higher CCS (%)	Higher Nuclear (%)
PAU yield	PAU	28	10	28	61
	50/50	22	8	22	48
Yield improvement	PAU	16	9	16	34
	50/50	12	7	12	26

3.3. Future land use change and distribution impact of the Carbon Plan pathways

The impact of the land required for bioenergy on future land use distributions in the UK is presented in Fig. 4. Differences in land use distribution amongst pathways and scenario combinations are a direct consequence of land allocation required to meet the projected demand for energy crop production and other land services, including housing and settlement, food production and forestry expansion. The most significant changes in land use are those associated with land for livestock and fibre, which mainly involve improved grassland and pasture. These changes are a result of conversion to other forms of land use, particularly energy cropping, but also housing and forestry. The scale of change however varies with crop composition and yield. The PAU crop composition and PAU yield scenarios presents the highest projected changes in land use by 2050 across all Carbon Plan pathways. Under this scenario, 17–85% of improved grassland and pasture is projected to change to bioenergy cropping and other land use demands (Fig. 4a). The lowest projected land use distribution changes are associated with the combination of the 50/50 crop composition and high crop yield scenarios (Fig. 4d). In these cases, conversion of improved grassland and pasture to bioenergy cropping and other land uses is projected to be between 10% and 26% by 2050. While these scenarios present the least potential future land stress of all pathways, the change is still significant.

3.4. Progress of deployment and 2030 targets

Trends of land appropriation for bioenergy production are presented in Fig. 5, together with the Bioenergy Strategy (DECC, 2012b) estimates of the range of UK land area that could be sustainably converted to indigenous bioenergy crops by 2030. This shows that the projected land appropriation for all pathways far exceed projections based on current rates of deployment, yield and crop composition. Additionally, land appropriation under most of the pathways (except Higher Renewable) are likely to significantly exceed the Bioenergy Strategy 2030 estimation of sustainable land-use change to bioenergy crops.

4. Discussion

The study has shown that although the Carbon Plan pathways have appear to deliver the 80% GHG reduction target of the UK by 2050 (HM Government, 2011), the projected use of bioenergy lead to significant land competition. This illustrates a fundamental mismatch between energy policy and physical limits of natural resource appropriation, and could undermine the attainment of GHG emissions target.

Four key features of energy system planning affect the overall impact on land use: (1) primary energy demand reduction; (2) allocation of bioenergy feedstocks to different end uses; (3) bioenergy feedstock sourcing (e.g. crops vs. waste); and (4) bioenergy feedstock origin (i.e. imported vs. indigenous). The

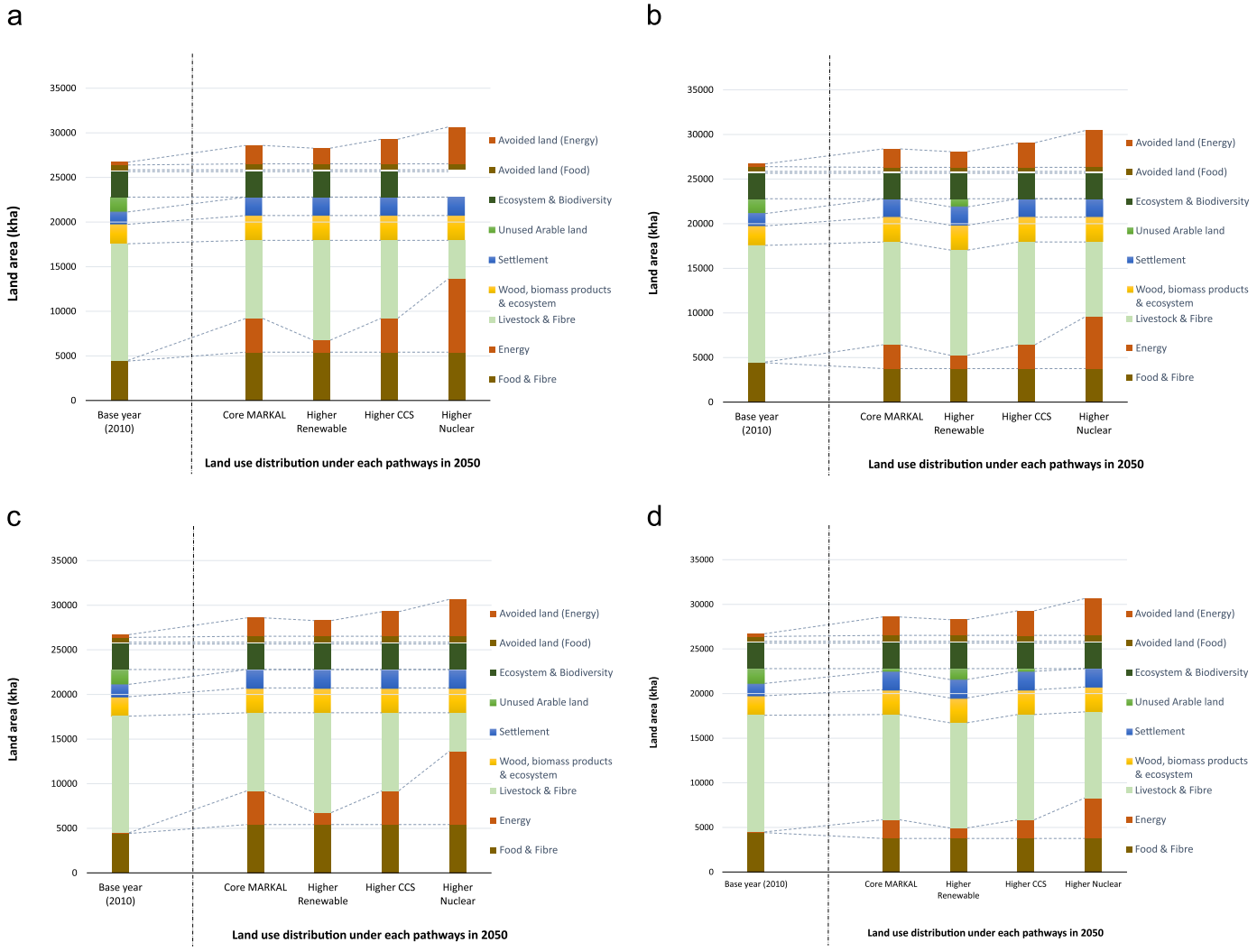

Fig. 4. (a) PAU second generation energy crop composition and PAU yield. (b) PAU second generation energy crop composition and improved yields. (c) 50/50 second generation energy crop composition and PAU yield. (d) 50/50 second generation energy crop composition and improved yield.

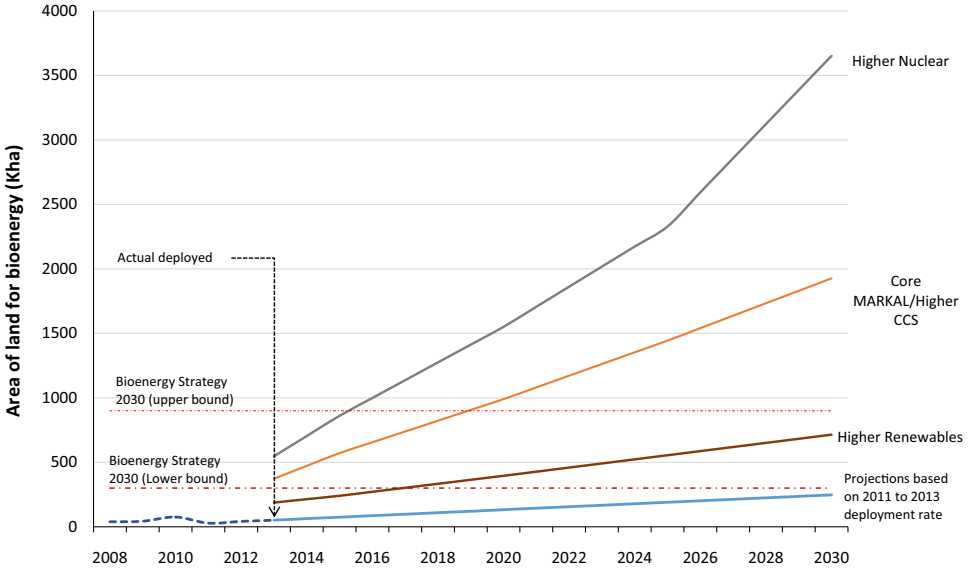

Fig. 5. Comparison of current actual trend of land deployment for bioenergy, the projected land deployment of Carbon Plan pathways by 2030 and the UK Bioenergy Strategy (2012) sustainable land use change to bioenergy thresholds.

primary energy demand is influenced by energy efficiency measures, while different routes of decarbonisation of the end use sectors determine the allocation of feedstock. The "Higher Nuclear, less energy efficiency" pathway which shows the highest land use impact, is the pathway with the highest share of bioenergy sources allocated to transport and industry in the form of liquid fuels (Fig. 1b), while simultaneously sourcing a significant share of these resources from 2nd generation UK crops (Fig. 1a). This is mainly due to the low efficiency of conversion of bioenergy feedstocks into liquid biofuels. Additionally this pathway has the least ambitious energy efficiency measures and lowest primary energy demand reduction. The "Higher CCS, more bioenergy" and "Core MARKAL" pathways have also been shown to have a significant impact on land use change. These two pathways have the same overall primary bioenergy demand in 2050, resource mix and origin, and thus have the same land use impact. The lower impact of these relative to the "Higher Nuclear, less energy efficiency" pathway is mainly linked to the decarbonisation options since these pathways have a higher proportion of bioenergy resources allocated to electricity and heat generation. The only Carbon Plan pathway with a low impact on land use, even if current yields of 2nd generation crops are maintained, is the "Higher Renewables, more energy efficiency" pathway. This is due to the combination of considerable reduction of overall primary energy demand, a lower share of bioenergy in the primary energy mix, and a more diversified strategy to end use sector decarbonisation.

Whilst some studies (e.g. Welfle et al., 2014) suggest that the UK could produce its entire bioenergy requirement without imports, this study suggests that not all Carbon Plan pathways can deliver this sustainably. According to Lovett et al. (2014), based on current UK and EU sustainability criteria, up to 30% of land across Great Britain could be available for perennial bioenergy crop production. This study has shown that, under the "Higher Nuclear, less energy efficiency" pathway, if current bioenergy crop yields persist, and the projected percentage of imported bioenergy feedstock remains the same, between 32% and 41% of UK land would indeed be required to meet bioenergy targets.

The challenges presented here relate mainly to land-use change, but the study also demonstrates a problem with crop-based bioenergy deployment targets based on recent land conversion rates. This reflects the adoption rate of bioenergy cropping by farmers relative to government targets. After allowing for imported bioenergy feedstock, the current pace of deployment of indigenously sourced bioenergy is inadequate to meet the 2030 UK Bioenergy Strategy aspirations. The implication of the estimates in this study is therefore that land availability and incentives for adoption of bioenergy cropping by farmers in the UK may undermine current energy policy aspirations. Moreover, a departure from the projected improvements in energy crop yield, which results in increased land area required for indigenous bioenergy production, could also result in increased GHG emissions from land use. This can consequently result in failure to meet GHG emissions targets. This is in addition to other economic and institutional barriers elaborated by Adams et al. (2011) such as: unproven and commercially unviable biomass technology; development and operational cost issues; and complex and costly range of legislations. These are beyond the scope of this study.

Apart from the indigenous bioenergy production and other land service dynamics discussed above, this study has also introduced the "avoided land" concept to account for other potential land use implications associated with bioenergy and food demand. This approach of analysing the UK import dependence, particularly of bioenergy and food, presents a way of incorporating the external land use and other environmental stresses resulting from imports, not usually accounted for in national environmental and GHG emissions assessments. The land, energy, GHG emissions, and water "footprints" of the UK should be properly assessed, as they have implications for environmental and other stresses elsewhere in the world.

5. Conclusion and policy implications

The main of this paper is that both the short term targets of the UK Bioenergy Strategy and long-term projections of bioenergy deployment in the Carbon Plan will probably lead to significant competition for land. Short-term measures to improve the current rate of bioenergy deployment are required if the Bioenergy Strategy 2030 targets for UK crop-based bioenergy are to be met. This suggests that the UK's 2050 GHG emissions targets would either be missed or more bioenergy would have to be imported. This would leave the UK's GHG targets at the mercy of international availability and market prices of feedstocks. Moreover, increasing feedstock imports would potentially cause additional land use change elsewhere. These notwithstanding, the study has also shown that pursuing an energy system pathway that has share of renewable resources, together with ambitious energy efficiency measures could deliver the targeted GHG emissions reduction in both the short- and long-term, with limited impact on the current UK land use system. However, as shown in Fig. 5, this will require significant improvement in crop yields together with a diversified energy crop composition.

It has been shown this paper that the current rates of bioenergy deployment, require a significant step-change in both demand and supply of indigenous feedstocks, if projected targets are to be met. This could perhaps be addressed by current institutional reforms in the UK energy sector, such as the Electricity Market Reforms (EMR) (DECC, 2015b) and the Renewable Heating Incentive (RHI) (DECC, 2015c), which envisage significant deployment of low-carbon energy technologies, including bioenergy. The planned investments and incentives in these policies present opportunities for expediting bioenergy deployment rates. For example, the electricity component of the 2020 DECC bioenergy consumption corresponds to the delivery plan of the EMR projections of bioenergy from biomass conversions, including dedicated Combined Heat and Power (CHP) biomass and small-scale dedicated biomass (DECC, 2015b). This adds more impetus to meeting the short term UK bioenergy deployment target through increased direct investments in the bioenergy sector under the EMR plans. However, with large up-front capital costs being a major barrier to adoption of domestic woodland systems by farmers in the UK (e.g. Feliciano, et al., 2014), it is imperative that incentives aiming to increase bioenergy deployment under the EMR and RHI cover both producers and consumers alike.

The study does not capture some fundamental elements of agricultural productivity, socio-cultural attachments to specific land use practices, and potential supply-chain bioenergy barriers to deployment. The biophysical factors that dictate land use and productivity (climatology, soil quality, and suitability for different crop types) are best analysed at field and regional levels. Furthermore, although motives for adopting a particular land use are mainly economic (Adams et al., 2011), there are also embedded spatially explicit and local socio-cultural factors that may present barriers to large-scale land-use change (e.g. Bürgi et al., 2004; Brown and Castellazzi, 2014). There are also local or regional logistical and infrastructural elements in the whole energy supply system that must be integrated with bioenergy development. Thus, whereas, a top-down approach provides interesting insights for shaping national policy, there is a parallel need for bottom-up approaches that focus on biophysical and socio-economic dynamics, as well as structuring an integrated supply chain to meet demand for implementation.

In conclusion, the study has shown that setting energy policy targets, while disregarding potential future land use evolution can lead to physically unfeasible land use requirements to accommodate future low-carbon energy system targets. Thus, achieving the bioenergy targets stipulated by the Carbon Plan or any other future energy system trajectory requires a major change in the way energy and land use policies are developed and implemented. This means that, the development of energy policies must take into account the potential future evolution of the land use system, which would lead to more feasible land requirement targets for the energy system.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2015.07.008.

References

Adams, P.W., Hammond, G.P., McManus, M.C., Mezzullo, W.G., 2011. Barriers to and drivers for UK bioenergy development. Renew. Sustain. Energy Rev. 15 (2), 1217–1227. http://dx.doi.org/10.1016/j.rser.2010.09.039.

Allwood J.M., Kopec G., Konadu D.D., Sobral-Mourao Z., Richards K., McMahon R., Fenner R., 2014. UK Energy, Water and Land Analysis (In Foreseer tool [computer software]). Available from: (⟨http://www.foreseer.group.cam.ac.uk⟩).

Aylott M., McDermott F., 2012. Domestic Energy Crops; Potential and Constraints Review. NNFCC. Available from: ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48342/5138-domestic-energy-crops-potential-and-constraints-r.PDF⟩ (accessed 12.02.15.).

Bürgi, M., Hersperger, A.M., Schneeberger, N., 2004. Driving forces of landscape change-current and new directions. Landsc. Ecol. 19 (8), 857–868. http://dx.doi.org/10.1007/s10980-005-0245-3.

Brown, I., Castellazzi, M., 2014. Scenario analysis for regional decision-making on sustainable multifunctional land uses. Reg. Environ. Change 14, 1357–1371. http://dx.doi.org/10.1007/s10113-013-0579-3.

Centre for Ecology and Hydrology (CEH), 2010. Land Cover Map 2007 (LCM2007). Available from: ⟨http://www.ceh.ac.uk/LandCoverMap2007.html⟩ (accessed 07.09.14.).

Committee for Climate Change (CCC), 2011. Bioenergy Review. Available from ⟨http://www.theccc.org.uk/publication/bioenergy-review/⟩ (accessed 24.08.14.).

Cullen, J.M., Allwood, J.M., 2010. The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy 38 (1), 75–81. http://dx.doi.org/10.1016/j.enpol.2009.08.054.

Department for Food, Environment and Rural Affairs (DEFRA) (formerly MAFF), 1988. Agriculture Land Classification for England. ©Crown copyright. Available from: ⟨http://magic.defra.gov.uk⟩ (accessed 17.09.14).

Department for Food, Environment and Rural Affairs (DEFRA), 2013. UK Agricultural statistics. ©Crown copyright. Available at ⟨https://www.gov.uk/government/collections/structure-of-the-agricultural-industry#2013-publications⟩ (accessed 07.10.14.).

Department for Food, Environment and Rural Affairs (DEFRA), 2014a. Overseas Trade in Food, Feed and Drink. ©Crown copyright. Available from: ⟨https://www.gov.uk/government/statistical-data-sets/overseas-trade-in-food-feed-and-drink⟩ (accessed 20.10.14.).

Department for Food, Environment and Rural Affairs (DEFRA), 2014b. UK Agricultural Statistics. ©Crown copyright. Available from: ⟨https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2013⟩ (accessed 27.11.14.).

Department of Energy & Climate Change (DECC), 2015b. Maintaining UK Energy Security: Electricity Market Reforms (EMR) (First Published in January, 2013) ©Crown copyright. Available from: ⟨https://www.gov.uk/government/policies/maintaining-uk-energy-security–2/supporting-pages/electricity-market-reform⟩ (accessed 12.01.15.).

Department of Energy and Climate Change (DECC), 2012a . Digest of UK Energy Statistics (DUKES) 2011. Available from: ⟨http://webarchive.nationalarchives.gov.uk/20130109092117/http://www.decc.gov.uk/en/content/cms/statistics/publications/dukes/dukes.aspx⟩ (accessed 16.12.13.).

Department of Energy and Climate Change (DECC), 2012b. UK Bioenergy Strategy. ©Crown copyright. Department of Energy & Climate Change URN: 12D/077. Available from: ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf⟩ (accessed 27.11.14.).

Department of Energy and Climate Change (DECC), 2014a. DECC Calculator Version 3.4.1. Available from: ⟨https://www.gov.uk/2050-pathways-analysis⟩, ⟨http://2050-calculator-tool-wiki.decc.gov.uk/pages/140#toc6⟩ (accessed 20.01.14.).

Department of Energy and Climate Change (DECC), 2014b. Digest of UK Energy Statistics (DUKES) 2013. Available from: ⟨https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes#2013⟩ (accessed 20.01.14.).

Department of Energy and Climate Change (DECC), 2015c. Increasing the Use of Low-carbon Technologies: Renewable Heat Incentive (2015). Available from: ⟨https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies/supporting-pages/renewable-heat-incentive-rhi⟩ (accessed 18.01.15.).

European Union (EU), 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the EU, L 140, June 5, 2009, pp. 16–62. Available from: ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF⟩ (accessed 14.07.13.).

Feliciano, D., Slee, B., Smith, P., 2014. The potential uptake of domestic woodfuel heating systems and its contribution to tackling climate change: a case study from the North East Scotland. Renew. Energy 72, 344–353. http://dx.doi.org/10.1016/j.renene.2014.07.039.

Fish, R., Winter, M., Lobley, M., 2014. Sustainable intensification and ecosystem services: new directions in agricultural governance. Policy Sci. 47 (1), 51–67. http://dx.doi.org/10.1007/s11077-013-9183-0.

Franks, J.R., 2014. Sustainable intensification: a UK perspective. Food Policy 47, 71–80. http://dx.doi.org/10.1016/j.foodpol.2014.04.007.

Hammond, G.P., Stapleton, A.J., 2001. Exergy analysis of the United Kingdom energy system. Proc. Inst. Mech. Eng. A: J. Power Energy 215, 141. http://dx.doi.org/10.1243/0957650011538424.

HM Government, 2008. Climate Change Act 2008 (c27). The Stationery Office Ltd., London.

HM Government, 2010. 2050 Pathways Analysis, Department of Energy and Climate Change. ©Crown Copyright. URN 10D/764. Available from: ⟨https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf⟩ (accessed 20.03.14.).

HM Government, 2011. The Carbon Plan: Delivering our Low Carbon Future, Department of Energy & Climate Change London, UK. ©Crown Copyright. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf (accessed 22.01.14.).

Holland, R.A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D., Taylor, G., 2015. A synthesis of the ecosystem services impact of second generation bioenergy crop production. Renew. Sustain. Energy Rev. 46, 30–40. http://dx.doi.org/10.1016/j.rser.2015.02.003.

Horrocks, C.A., Dungait, J.A., Cardenas, L.M., Heal, K.V., 2014. Does extensification lead to enhanced provision of ecosystems services from soils in UK agriculture? Land Use Policy 38, 123–128. http://dx.doi.org/10.1016/j.landusepol.2013.10.023.

Jablonski, S., Strachan, N., Brand, C., Bauen, A., 2010. The role of bioenergy in the UK's energy future formulation and modelling of long-term UK bioenergy scenarios. Energy Policy 38 (10), 5799–5816. http://dx.doi.org/10.1016/j.enpol.2010.05.031.

Lovett, A., Sünnenberg, G., Dockerty, T., 2014. The availability of land for perennial energy crops in Great Britain. Glob. Change Biol. 6 (2), 99–107. http://dx.doi.org/10.1111/gcbb.12147.

Ma, L., Allwood, J.M., Cullen, J.M., Li, Z., 2012. The use of energy in China: tracing the flow of energy from primary source to demand drivers. Energy 40 (1), 174–188. http://dx.doi.org/10.1016/j.energy.2012.02.013 1.

Milner, S., Holland, R.A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S., Taylor, G., 2015. Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. GCB Bioenergy . http://dx.doi.org/10.1111/gcbb.12263, published online.

Office of National Statistics (ONA), 2014. UK National Population Projections-Principal and Variants, 2012–2087. Available from: ⟨http://www.ons.gov.uk/ons/interactive/uk-national-population-projections—dvc3/index.html⟩ (accessed 12.01.15.).

Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M., 2014. The effect of bioenergy expansion: food, energy, and environment. Renew. Sustain. Energy Rev. 32, 559–578. http://dx.doi.org/10.1016/j.rser.2014.01.056.

AEA, 2014. Review and synthesis of bioenergy and biofuels research. Report for DEFRA. Ricardo-AEA/R/ED59367. Available from ⟨http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=19177⟩ (accessed 27.04.15.).

Rowe, R.L., Street, N.R., Taylor, G., 2009. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renew. Sustain. Energy Rev. 13 (1), 271–290. http://dx.doi.org/10.1016/j.rser.2007.07.008.

Rowe, R.L., Goulson, D., Doncaster, C.P., Clarke, D.J., Taylor, G., Hanley, M.E., 2013. Evaluating ecosystem processes in willow short rotation coppice bioenergy plantations. Glob. Change Biol. 5 (3), 257–266. http://dx.doi.org/10.1111/gcbb.12040.

Soil Survey of Scotland Staff, 1981. Land Capability for Agriculture maps of Scotland

at a Scale of 1:250,000. Macaulay Institute for Soil Research, Aberdeen.
Smith, P., Gregory, P.J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Wood, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. B 365 (1554), 2941–2957.
Thornley, P., Upham, P., Tomei, J., 2009. Sustainability constraints on UK bioenergy development. Energy Policy 37 (12), 5623–5635. http://dx.doi.org/10.1016/j.enpol.2009.08.028.
US Department of Energy (DOE)/Oak Ridge National Laboratory (ORNL) Biomass Energy Data Book, 2011. Available from: ⟨http://cta.ornl.gov/bedb/appendix_a/Heat_Content_Ranges_for_Various_Biomass_Fuels.pdf⟩ (accessed 27.08.14.).
Warwick, H.R.I., Park, N.S., 2007. AC0401: Direct Energy Use in Agriculture: Opportunities for Reducing Fossil Fuel Inputs. University of Warwick, Warwick.
Welfle, A., Gilbert, P., Thornley, P., 2014. Securing a bioenergy future without imports. Energy Policy 68, 1–14. http://dx.doi.org/10.1016/j.enpol.2013.11.079.
Welsh Government, 2010. Agriculture Land Classification for Wales.
Wilson, J.B., Peet, R.K., Dengler, J., Pärtel, M., 2012. Plant species richness: the world records. J. Veg. Sci. 23 (4), 796–802. http://dx.doi.org/10.1111/j.1654-1103.2012.01400.x.