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Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK

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Abstract

There is momentum, globally, to increase the use of plant biomass for the production of heat, power and liquid transport fuels. This review assesses the evidence base for potential impacts of large-scale bioenergy crop deployment principally within the UK context, but with wider implications for Europe, the USA and elsewhere. We focus on second generation, dedicated lignocellulosic crops, but where appropriate draw comparison with current first-generation oil and starch crops, often primarily grown for food.

For lignocellulosic crops, positive effects on soil properties, biodiversity, energy balance, greenhouse gas (GHG) mitigation, carbon footprint and visual impact are likely, when growth is compared to arable crops. Compared to replacement of set-aside and permanent unimproved grassland, benefits are less apparent. For hydrology, strict guidelines on catchment management must be enforced to ensure detrimental effects do not occur to hydrological resources. The threat of climate change suggests that action will be required to ensure new genotypes are available with high water use efficiency and that catchment-scale management is in place to secure these resources in future. In general, for environmental impacts, less is known about the consequences of large-scale deployment of the C4 grass Miscanthus, compared to short rotation coppice (SRC) willow and poplar, including effects on biodiversity and hydrology and this requires further research.

Detailed consideration of GHG mitigation and energy balance for both crop growth and utilization suggest that perennial crops are favoured over annual crops, where energy balances may be poor. Similarly, crops for heat and power generation, especially combined heat and power (CHP), are favoured over the production of liquid biofuels. However, it is recognized that in contrast to heat and power, few alternatives exist for liquid transportation fuels at present and research to improve the efficiency and energy balance of liquid transport fuel production from lignocellulosic sources is a high current priority.

Although SRC, and to a lesser extent energy grasses such as Miscanthus, may offer significant benefits for the environment, this potential will only be realized if landscape-scale issues are effectively managed and the whole chain of crop growth and utilization is placed within a regulatory framework where sustainability is a central driver. Land resource in the UK and throughout Europe will limit the contribution that crops can make to biofuel and other renewable targets, providing a strong driver to consider sustainability in a global context.

Keywords: Bioenergy crops; Soil carbon; Biodiversity; Hydrology; Greenhouse gas mitigation; Biofuel

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1. Introduction

Energy from green plants has much to offer, being renewable and largely carbon neutral in comparison to fossil fuel combustion. Pacala and Socolow [1] suggest that replacement of fuel from fossil sources with that of biological sources could provide one ‘stability wedge’ contributing to reduced carbon emission rate, but also note that this is not without implications for biodiversity and land-use, globally. Here, we explore the potential environmental impacts of increased deployment of dedicated biomass crops for heat, power and liquid biofuel supply, in a UK context but with wide implications across Europe and other temperate agricultural regions. We define dedicated bioenergy crops as those, annual or perennial, grown for the specific purpose of energy and not food production. This is focussed largely on woody crops of willow (*Salix* spp.) and poplar (*Poplus* spp.) and energy grasses such as Miscanthus. Annual crops including sugar beet, cereal crops and oil seed rape that may be processed for bioethanol and biodiesel, respectively, are also considered with respect to energy balance, with other reviews dealing with their agronomy and wide environmental impacts. The policy drivers, potential biomass resources and predicted changes in land use are considered in the context of likely environmental impacts, and in particular visual impact, soil carbon sequestration, nitrogen leaching, soil erosion, biodiversity, hydrology and carbon footprint.

Within the UK targets set out in the Energy White Paper for a reduction of CO_2 emissions to 20% of 1990 concentrations by 2010, rising to 60% by 2050 [2], have provided a strong policy driver for the development of the renewable energy sector. However, if these targets are to be met the contribution of renewable energy to power

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generation will need to rise considerably, from approximately 3.1% to 20% by 2020 [2,3]. As one possible source of renewable energy, biomass has been recognized as a key resource for future energy supplies [4]. Indeed the Royal Commission on Environmental Pollution [4] suggested that by 2050 up to 12% of the UK's energy (excluding transport) could potentially be supplied from biomass derived energy production. At the European level, it has been suggested that up to 14% of liquid transport fuel demand could be met from biological sources by 2020 [5]. Biomass has advantages over other renewable resources as it does not suffer from intermittency of supply, and in the case of liquid fuels few other options are available in the short-to-medium term future [4,6]. The UK has become the first Government globally to make a legal commitment to reduce CO_2 concentrations, placing it at the forefront of the nations committed to developing a low carbon economy, as exemplified by the recent Stern review [7].

The Renewable Obligation Order 2005 has provided much of the incentive for the use of biomass for power generation. Under this legislation, power generators in the UK are required to produce 6.7% of their energy from renewable sources in 2006/2007, rising to 15.4% in 2015/2016 [4], with power generators awarded renewable obligation certificates (ROCs) for every MWh they produce from renewable sources, that may then be presented to meet the obligation, or traded with other generators [8]. This legislation has lead to the development of small-to-medium-sized dedicated biomass fired burners, combined heat and power (CHP) plants and especially large-scale co-firing, in which biomass is utilized alongside fossil fuel in conventional power stations. In addition, a recent consultation document on the future of the renewable obligation and ROCs has outlined the government desire to bring in a banding system for ROCs, which would see an extension to the current ROC system, beyond its current 2016 end date [8]. Within the transport sector in line with EU Biofuel Directive 2003/30/EC [9], the renewable transport fuel obligation requires that 5.75% v/v of all transport fuels sold across the EU are biomass derived by 2010, providing an incentive for the development of biodiesel and bioethanol plants within Europe.

Despite this positive outlook, several issues remain unresolved with respect to the large-scale deployment of bioenergy crops. Public perception of biomass combustion is often negative, due to perceived associations with 'waste', 'incineration' and 'pollution' [10]. Large-scale deployment of bioenergy crops would require landscape-scale change and the social and environmental impacts of such a change are not yet adequately understood or accepted. Indeed there is considerable controversy over how the available land resource in the UK could accommodate a significant development in dedicated bioenergy crops given current, and particularly, future demands for food production in the face of climate change. Similar debate is raging across the EU [11], the USA [12] and globally [13]. Therefore, we also explore land-use and biomass supply potential. Finally, where the current evidence base does not enable an appropriate policy and legislative framework to be developed, we provide some recommendations for further research.

2. Sources of biomass in the UK

Biomass derived feedstock's fall into two principle categories; those used for power (heat and electricity) production, and those used to produce liquid transport biofuels. The development of novel processing methods such as lignocellulosic fermentation and the biorefinery concept—the production of multiple outputs from a single biomass feedstock are likely to eliminate this duality for certain crops within the next 10–15 years [14,15].

2.1. Biomass for power generation

2.1.1. Short rotation coppice (SRC) willow or poplar

High-density plantations of around 15,000 stools ha^{-1} of willow or 10–12,000 stools ha^{-1} of poplar established from hardwood cuttings, taken from a range of commercially available clones. Plantation establishment involves winter–spring planting of cuttings followed by a first-year growth as single stems. In the following winter, these single stems are cut back to ground level to encourage the production of multiple stems, resulting in the development of dense plantations of multi-stemmed stools [16]. The above-ground biomass is then harvested typically every 3 years [16]. Harvested material is chipped and dried ready for use in either dedicated biomass burners or for co-firing. Each plantation can remain viable for between 25 and 30 years with yields of between 7 and 12 oven dried tonnes (ODT) $ha^{-1}\,year^{-1}$ [16]. Willow SRC is currently grown more extensively than poplar but both have been trialled across the UK [10].

2.1.2. Miscanthus

A tall woody perennial grass, native to Asia, miscanthus is capable of fast growth reaching heights of 2.5–3.5 m in a single year [17]. Planting material is either derived from rhizome division or micropropgagtion, with rhizome division being the favoured method [17]. Rhizomes are planted at a density of around 20,000 plants ha^{-1}, and the resulting growth can be harvested annually between January and March, with individual plantations remaining viable for at least 15 years [17]. Yields from experimental plots within the UK have exceeded 13 dry t $ha^{-1}\,year^{-1}$, and as with SRC the biomass can be utilized in either deciated biomass plants or for co-firing [17]. Switch grass (*Panicum virgatum*), and canary reed grass (*Phalaris arundinacea*) also represent viable grass biomass crops within the UK. Miscanthus is, however, widely considered to be superior to these grasses in the UK climate [4].

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2.1.3. Waste

In addition to dedicated crops, there are a number of other biomass sources that can be used for energy production including a number of 'waste' products [4]. 'Waste' includes agricultural residues such as straw, chicken manure and sugar beet tops; forestry waste such as sawmill waste and available standing wood in excess of demand; and municipal waste from the maintenance of parks, railways and highways [4]. The use of these waste products is likely to be important in the future, since they represent several million tonnes of available biomass resource [18].

2.2. Biomass for liquid transport biofuels

2.2.1. Wheat and sugar beet

Wheat grain and sugar beet can be processed by fermentation of the starch and sugars respectively, followed by distillation to produce bioethanol. The bioethanol produced is mixed with petrol, and up to an inclusion rate of 5% requires no engine modification. However, appropriate modification can allow inclusion rates of 22%, or even up to 75–95% in highly modified engines. [15]. Within the UK both Wessex Grain and British Sugar are in the process of constructing bioethanol plants using cereal grain and sugar beet respectively, as feedstocks, with a combined predicted output of 211M l year^{-1} [19,20] (Table 1).

2.2.2. Oilseed rape

Vegetable oil produced from oilseed rape can be converted through a process of esterification to biodiesel. This fuel can be used as a complete replacement for diesel, although engine manufactures currently only warrant 5% inclusion rate [15]. In fact, a range of vegetable and animal oils and fats can be used as a feedstock for this process, however oilseed rape is currently the most feasible crop, from a processing perspective [15]. Within the UK Greenergy are currently constructing a biodiesel plant capable of producing 228M l of biodiesl per year at Immingham with another plant planned for Liverpool [21] (Table 1).

2.2.3. SRC, Miscanthus and straw

New methods are currently under development which will enable the processing of lignocellulosic biomass (such as wood and grasses) to produce either bioethanol or complete fuel replacement [22]. These include lignocellulosic fermentation which utilizes lingocellulosic crops to produced bioenthanol, and pyrolysis which yields bio-oil which can then be refined to produce a complete fuel replacement [22]. However, commercial scale operation of these technologies is not yet developed within the UK.

3. UK land requirements

To meet the predicted increase in demand for biomass derived renewable energy will require significant changes in current land use, to ensure adequate feedstock production. It has been suggested that to meet carbon emissions targets for 2010 a land area equivalent of 7% of the UK's agricultural land would be required for the production of energy crops for electricity, heat and transport [23]. With current agricultural land area of 18M ha this equates to around 1.3M ha assuming current yields (Fig. 1) [23,24].

3.1. Power generation

Considering power generation alone, a report by the House of Lords, Science and Technology Committee predicted that in 2010 between 125,000 and 175,000 ha would be required for the production of energy crops, with this growing to 350,000 ha in 2020. There was a further assumption that around 70% of generation would be produced from SRC and Miscanthus [24] (Fig. 1). This is a large increase from the 7320 ha of SRC and Miscanthus grown in England, Scotland and Wales in 2006 [25,26]. In the longer term RCEP, 22nd report gives four possible

Table 1
Commercial UK biofuel projects

Company	Description	Capacity	Current status	Ref.
British sugar	Bioethanol plants utilizing sugar beet, Wissington, Norfolk	70M l per annum	Construction initiated in January 2006, completion expected February 2007	[a]
Greenergy	Biodiesel plant, Immingham	Initially, 114M l per annum rising to 228M l	Construction completion expected end of 2006	[b]
Green sprit fuels (Wessex Grain company)	Bioethanol Plant, utilizing wheat grain, Henstridge, Somerset	141M l per annum	Construction completion expected in 2007	[c]

[a] http://www.britishbioethanol.co.uk/IsolatedStorage/94175874-67b5-4c33-9f38-380233f14049/ContentAssets/Documents/Bioethanol/Media/planthandout.pdf

[b] http://www.greenergy.co.uk/company/biodiesel_business.html

[c] http://www.greenspiritfuels.com/about.htm

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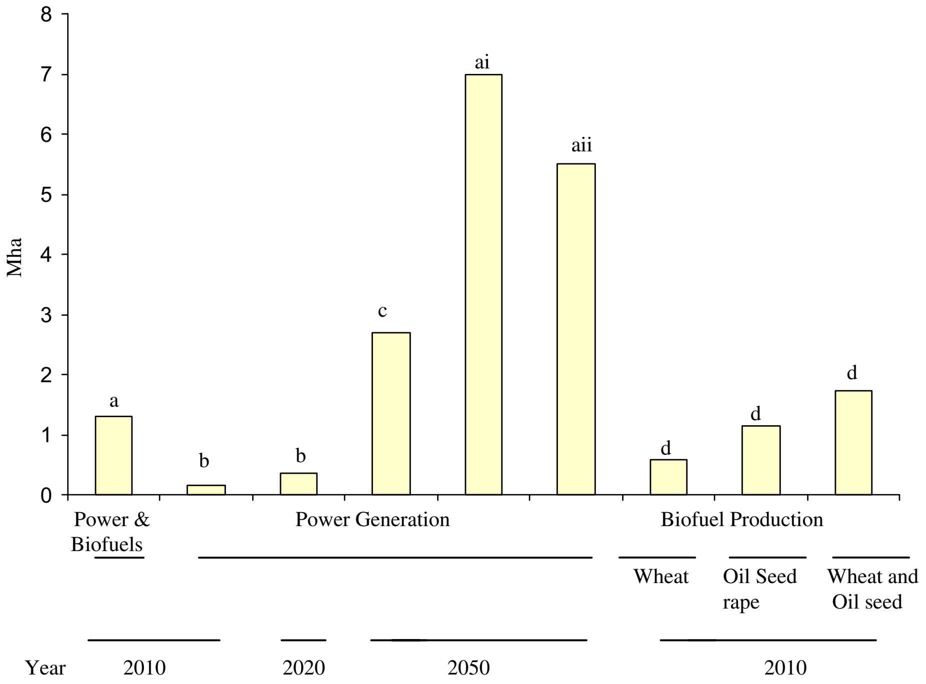

Fig. 1. Predicted land requirements in the UK for future biomass and biofuel production: (a) DTI report, A strategy for non-food crops and uses: Creating value from renewable materials [23] ai: Supply from wood biomass only, aii Supply required if forestry and agricultural waste also utilized. (b) House of Lords, Science and Technology Committee, 4th report of session 2003–2004, Renewable Energy: Practicalities Volume I: Report [24]. (c) Royal Commission on Environmental Pollution: 22nd Report, Energy—The changing climate [27]. (d) Low carbon vehicle partnership, biofuels for road transport [28].

scenarios for power supply in 2050, all of which include the use of biomass CHP generation [27]. Under the most ambitious scenario, the cultivation of energy crops (most likely SRC) would require a land area equivalent to 15% of the UK's current farmland, equating to around 2.7M ha [27]. In more extreme scenarios, it has been suggested that up to 7M ha of woody crops would be required to meet targets of 16 GW of electricity form biomass by 2050, if this was the sole source of supply (Fig. 1) [4].

Such ambitious targets represent a large part of the UK agricultural land resource and are probably unrealistic, highlighting the need for a diverse energy portfolio of renewable resources and the development of high yielding dedicated bioenergy crops (Fig. 2).

3.2. *Biofuels*

Several recent studies have considered the production of liquid biofuels and the UK commitment to the renewable fuels obligation [23,28,29]. It is estimated that to meet the target of 5.75% v/v inclusion rate by 2010, around 0.36M ha of wheat and 0.23M ha sugar beet would be required for production of bioethanol, with a further 1.15M ha of oilseed rape for the production of biodiesel (Fig. 1) [28]. Currently, around 3M t of wheat grain is exported every year and it has been suggested that reallocation of this to bioethanol production would meet demand for this fuel source without any need for changes in land use [29].

3.3. *Land utilization*

Although not all energy crops would result in changes in land use, as crops such as wheat and oilseed rape can be utilized as energy crops [23], it is clear that significant increases in land area devoted to energy crops will be necessary. Some of the land required could come from the redeployment of current set-aside, as the common agriculture policy single payment scheme allows land owners to continue receiving set aside payments for land planted with energy crops [30]. However, set-aside alone will not be enough to meet the cropping area required, (Fig. 2) nor will all of it be suitable for the production of bioenergy crops. The conversion of arable and grassland to biomass and biofuel crop production is therefore likely, if predicted demand is to be met.

4. Visual impacts

The visual impacts of liquid biofuel crops are likely to be limited as these crops are already widely grown and accepted within the countryside setting [15]. In contrast, the visual appearance of SRC and, Miscanthus contrast significantly to traditional crops and will be the focus here.

4.1. *SRC and Miscanthus*

The visual appearance of SRC plantations changes as the crop matures: in the early stages just after harvest or

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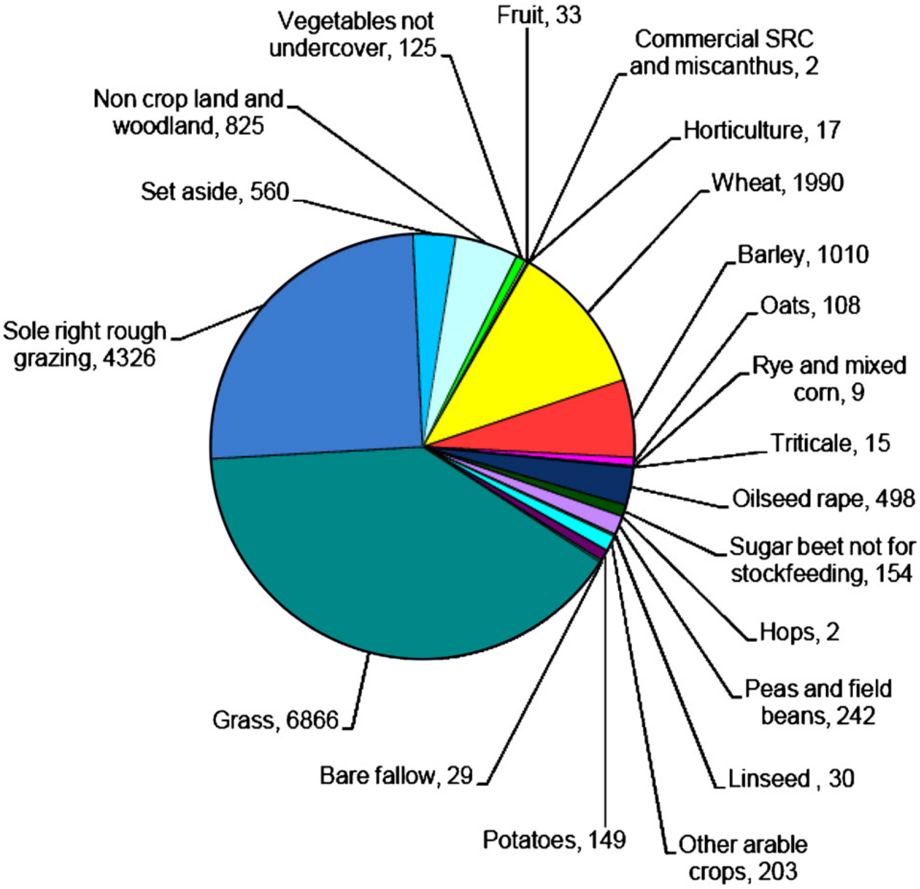

Fig. 2. UK Agricultural Land Use in 2004 (thousands of hectares), taken from a variety of sources [103].

establishment the appearance of the plantation is comparable to other arable crops. As the plantation grows, it quickly develops more individual characteristics unlike any other arable crop or natural vegetation and once fully mature, has the appearance of a thicket forest reaching heights of 5–6 m [31]. The main concerns in relation to the visual impact of SRC are the obscuring of landscape features, obstruction of views, impacts on scenic quality and rapid changes in visual appearance caused by harvesting [31,32]. Investigations conducted in Sweden and the UK have concluded that visual impacts of SRC plantations can be limited by adjusting the scale and shape of plantations to blend with dominant landscape features, with sites located in lowland arable landscapes with high levels of forest cover resulting in the lowest visual impact [31–34]. In addition, the complementary planting of shrubs or native trees can be used to limit the effect of sudden changes in landscape during harvesting, especially near to residential buildings [33].

The visual impact of Miscanthus has received less attention, perhaps reflecting the lower crop height in comparison to SRC of 3.5 m, and the more traditional harvest cycle and appearance of Miscanthus [17]. Advice on the selection of sites for Miscanthus plantations is in most regards identical to that for SCR plantations, with the overall aim being to blend the crop into the current landscape [35].

Regulations within the UK require an assessment of the potential visual impacts of many SRC plantations, such as the Environmental Impact Assessment (Forestry) (England and Wales) Regulations 1999 and Environmental Impact Assessment (uncultivated land and semi-natural areas) (England) Regulations 2001. Further assessments are also required when applying for grant schemes for both SRC and Miscanthus [35]. Despite this level of advice and regulation a study of 13 SRC plantations found that four sites (31%) resulted in adverse effects on the quality of the visual landscape [32]. However, this same study suggested that in certain landscapes SRC and Miscanthus could actually serve to increase visual interest [25].

As it seems unlikely that the predicted scale of SRC and Miscanthus plantations can be achieved without some detrimental visual impact, successful implementation may only be achieved through careful planning coupled with increase public awareness and consultation.

5. Impacts on soil

The production of crops used for biofuels such as cereals and oilseed rape is likely to cause limited changes in the condition and status of agricultural soils, as production

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methods will remain unchanged. Therefore, this section focuses on the effect of SRC and Miscanthus on soils compared with other land uses.

5.1. Soil carbon

Purely in terms of changes in soil carbon (soil organic carbon (SOC)), excluding any sequestration in living biomass (soil organic matter (SOM)), a recent model of the potential for carbon sequestration in SRC willow plantations suggests that within the UK, increases in SOC under SRC could alone contribute around 5% of the carbon mitigation benefits of this crop. This was supported by a USA-based study of poplar plantations, in which the author suggest that after an initial period of loss, carbon sequestration could be expected to result in gains equivalent to 1–1.6 t C ha^{-1} $year^{-1}$ over a 10–15-year period [36].

However, other studies provide mixed findings [36–40]. For example, an investigation on SOC sequestration at three sites in Germany (each with plots of SRC willow, poplar and aspen) reported an increase in SOC at one site of 20% compared to arable land, due mainly to increases in C in the top 10 cm of soil [41]. However, at the other two sites no overall increase in SOC was seen, as increases in SOC in the top level of soil was balanced by a decrease in levels below 10 cm. A similar pattern was also seen in the study on SRC willow and poplar by Makeschin [39,41]. This study also included a site on former grassland in which a loss of 15% of original SOC was reported, suggesting that former land use, and thus initial SOC levels, need to be considered when locating SRC plantations [41].

In the case of Miscanthus, mixed results of the effect of this crop on SOC have also been seen. Of the four sites investigated in one study two showed an increase in SOC compared to adjacent grassland areas, while two showed no signification effect [40]. Importantly, the sites that did show an increase, were based on sandy soils compared with silty clay in the other two sites suggesting soil texture is an important factor [40]. More recently a study in Denmark utilized C^{13}/C^{12} ratios to compare carbon sequestration in 9- and 16-year-old Miscanthus plantations to adjacent grass and arable row crops. Levels of SOC where only higher in the 16-year-old plantation compared with the control crops; however, the C isotope data clearly showed that carbon from the Miscanthus accounted for a significant fraction of the SOC pool as after 9 and 16 years 13% and 31%, respectively, of the SOC present at 0–20 cm was derived from Miscanthus [42]. Levels for deeper soil fractions were lower. However, the overall input of C from Miscanthus to the top 100 cm of soil equated to between 0.78 and 1.13 t C ha^{-1} $year^{-1}$.

The variable nature of the results for SOC sequestration are generally attributed to the sensitivity of carbon sequestration to a number of factors including climate, annual precipitation, soil texture and initial soil carbon content [36,38,43]. Tests using the Grogan and Matthew model [38] highlighted the sensitivity of carbon sequestration to initial soil carbon, with a strong negative correlation apparent, a factor which together with soil texture has also been reported to be important in experimental data [40,41].

Despite these variations there is a general consensus that the conversion of arable land to SRC or Miscanthus will result in an increase in carbon sequestration, while the conversion of grassland may not be as beneficial. This view was echoed by King et al., who suggest that while conversion of arable land to SRC willow or Miscanthus will result in increase in SOC of 0.55–0.83 t C ha^{-1} $year^{-1}$ and 0.49–0.73 t C ha^{-1} $year^{-1}$, respectively, conversion of grassland to either of these crops can not be expected to increase SOC [44]. It is also important to note that in all cases, soil carbon concentrations will not increase indefinitely, as eventually a new higher carbon equilibrium will be achieved, although it is not clear how long this process will take [39,40].

5.2. Soil condition

Increases in SOC in relation to the establishment of SRC and Miscanthus plantation are also linked to wider improvements in soil condition including improved soil texture, water retention and fertility as a result of reduced tillage, and increases in litter inputs and SOM [37,39,45,46]. A study of four Miscanthus plantations in Germany, for example, reported an increase in SOM storage in topsoil of 11.7 t ha^{-1} compared to the grassland control over 4 years [40]. In addition, the SOM in Miscanthus plots was enriched with lipids, sterols and free fatty acids and lower in nitrogen containing compounds. This resulted in increased hydrophobicity, and a potential for improved physical soil properties due to the role these compounds play in soil aggregate formation and stability [40]. In addition the extensive roots systems characteristic of willow, poplar and Miscanthus result in large below ground biomass storage, further improving the carbon mitigation potential of these plantations in addition to improving soil texture, with estimated levels carbon storage of between 5 and 12 t C ha^{-1} over the 25-year life cycle of the crop [37,47].

5.3. Nitrogen

The extended growing season, high evapotranspiration rates and extensive root systems of SRC and Miscanthus plantations has lead to much interest in the effect these plantations may have on nitrogen cycling, leaching and related changes in water quality [37,48,49]. Indeed, a study on unfertilized SRC poplar and willow plantations reported reduced nitrate leaching of around 25 kg N ha^{-1} $year^{-1}$ compared with intensively managed agricultural land, with a further reduction in nitrate leaching of around 50% compared with arable land predicted for the proceeding 3 years [39]. However, in order to maintain yields with current genotypes it is likely that commercial SRC crops will be fertilized, with recommend yearly application for SRC plantations of around 100 kg N ha^{-1}, and 88 kg N ha^{-1} for Miscanthus [16,17]. In the long term, research is aimed at providing new genotypes that require limited N inputs.

The potential effect of fertilization of SRC willow plantations has been investigated in some detail as willow is known to have a high nitrogen uptake capacity indeed there have been several studies on the potential of using these crops to remove nitrates from waste water [48,50]. Aronsson and Bergstrom [50] investigated the effect of fertilization with simulated waste water on nitrate leaching from SRC willow and found that while nitrate leaching did occur in the first 2 years of establishment, in the third year nitrate leaching was low or negligible. Maximum losses in the third year of only 9.7 kg N ha^{-1} year^{-1} were recorded even with nitrate application rate of 220–244 kg N ha^{-1} year^{-1}, with plots receiving less dilute nitrate solution recording even lower losses of under 1 kg N ha^{-1} year^{-1} [50]. Similar results were also seen in a longer 9-year study of SRC willow, in which leaching levels of 1.6 kg N ha^{-1} year^{-1} where recorded under fertilization application rates ranging from 90 to 127 kg N ha^{-1} year^{-1} [48]. These figures are considerably lower than the averages of 58 kg N ha^{-1} and 30 kg N ha^{-1} year^{-1} reported for conventionally managed arable crops [51,52]. Aronsson and Bergstom [50] caution that under commercial conditions the levels of nitrogen that could be applied without significant leaching would be lower. However, they estimated that 160–190 kg N ha^{-1} year^{-1} could be applied with no appreciable leaching from the third year onwards, well above the level recommended to maintain growth [16,50].

Fewer studies have been carried out on Miscanthus. Christian and Riche [53] found relatively high nitrate leaching in the first year of Miscanthus establishment but by the third year winter losses fell to 3, 11 and 30 kg N ha^{-1} with fertilization rates of 0, 60 and 120 kg N ha^{-1}, respectively, suggesting that, like SRC plantations, Miscanthus can lead to reduced nitrate leaching compared with arable crops post establishment. However, the effect of plantations on the nitrogen status of the soil is dependent on original soil status, for example, Jug et al. [41] demonstrated that while planting SRC on ex-arable land resulted in no changes in soil nitrogen levels, planting on ex-grassland resulted in a loss of nitrogen, caused by increased microbial activity and nitrogen mineralization at a rate in excess of plantation requirements [41]. Even considering these factors, Borjesson [37] estimates that a 50% reduction in nitrogen leaching over 60% of Swedish arable land would be possible by the establishment of SRC and Miscanthus plantations, with further benefits arising if these plantations are used as buffer strips alongside watercourses, suggesting that within the UK these crops may have similar benefits [37].

5.4. *Erosion*

Soil erosion leads to the degradation of soil quality, fertility and productivity [54]. Soil erosion can have negative effects on watercourses as a consequence of increased sediment and nutrient loading [54]. While agricultural land used for row crops is particularly susceptible to erosion, the year round cover, extensive rooting systems and increased level of interception provided by SRC and Miscanthus is expected to reduce erosion risks [54,55]. Willow and poplar have for some time been used in New Zealand to reduce erosion, with their extensive and fast growing root systems recognized as important characteristics, reducing bank erosion [56]. In addition while there is some concern that soil exposure during establishment of SRC plantations may lead to increased erosion, the increased evapotranspiration rates and improved soil infiltration observed in mature SRC plantations leads to reduced run-off and thus decreased erosion [55]. In the case of Miscanthus, studies in the USA have shown that erosion rates under perennial grasses are significantly reduced compared with arable row crops [55].

5.5. *Phytoremediation*

The use of energy crops and especially SRC plantations in phytoremediation of contaminated soil and water is a rapidly developing field and represents an important environmental co-benefit worthy of careful consideration [57]. Of the possible applications the use of SRC willow to remove nitrates and other nutrients from municipal waste water (also referred to as ‘polishing’), farmland drainage water and sewage sludge, is the most widely researched area and shows the greatest potential [48,50,57]. Waste water polishing represents a potential win–win situation: offering a cheap alternative to traditional sewage treatments, and providing an ideal fertiliser and water supply for the energy crops, resulting in improved yields [50,57–59]. Application rate of waste water of up to 20 mm day^{-1} have been shown to increase yield in small scale trials of SRC willow plots, at larger scale a reduced rate of 6 mm day^{-1} was found to be optimum equating to 166 kg N over the growing season (May–October) [60].

Extensive research has also examined the feasibility of using SRC plantations for the treatment of contaminated soil, especially the removal of cadmium. Willow naturally accumulates Cd; thus through the normal process of harvesting and burning, with the addition of scrubbing of flue gasses, SRC willow can provide a cost effective way of treating contaminated land [58]. Within the UK, studies on contaminated brown field sites found that mixed poplar and willow SRC together with *Alnus* species were effective in reducing Zn and Cd levels, with the authors suggesting that over a 20-year period the most effective variety, *Salix × Calodendron*, could reduce Cd and Zn levels by 5.6 and 96 mg kg^{-1}, respectively [61]. In addition, poplar genotypes

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have also been found to aid the breakdown of a range of other pollutants including trichloroethylene (TCE), atrazine, dioxane, TNT and methyl-tertiary-butyl-ether [62–65].

In Belgium, the use of willow to treat sediment dredged from rivers has also been investigated: in addition to toxic metals this sediment also contains mineral oil and polycyclic aromatic hydrocarbons (PAH) [66]. Managed in a similar way to conventional SRC plantations, high density stands of willow increased the rate of degradation of mineral oil, with a 57% reduction in trial site compared to 15% in control plot. The results of PAH degradation were less encouraging with reduced rates under willow compared with barren control [66]. More recently, the possibility of using willow to treat landfill leachate has been investigated, since current treatment methods are costly and require high maintenance. These plantations have been effective in reducing levels of leachate contamination with reductions in ammonia, total nitrogen, phosphate levels and biological oxygen demand of up to 99.9%, 93.3%, 95% and 94%, respectively, being reported [60]. The high evapotranspiration rate of the willow also reduces the volume of leachate [60,67].

The use of other energy crops for these applications has not been investigated and it seems unlikely that they could provide such multi-function possibilities.

6. Impacts on biodiversity

6.1. SRC and flora diversity

Flora diversity in SRC plantations has been examined in a number of studies. Cunningham et al. [68] found that over a 4-year period in which flora diversity and abundance was monitored in 12 SRC willow plantations and arable controls, that SRC consistently contained higher species richness and abundance in comparison to arable controls. A total of 133 plant species were recorded in SRC compared to 97 species in arable controls. The SRC headlands (11.24 species per 10 m^{-2}) also contained more species than headlands of conventional crops (9.98 species per 10 m^{-2}). The authors to suggest that SRC plantations can increase farmland flora diversity compared with arable crops—a view also supported by a range of studies within the UK and Europe [69–71].

There has also been considerable interest in how the ground flora within SRC develops over time, and what type of stable community will result. Sage et al. [70] examined ground flora in 21 UK sites of SRC previously studied in 1993, an approach that allowed the comparison of the flora community development over time [70,72]. Most of the species recorded were common and widespread species (Table 2), with young plantations characterized by tall herb communities dominated by competitive ruderal (C–R) (sensu Grimes 1988) and competitive stress tolerate ruderal (C–S–R) species. Over the three years between surveys, the plant community shifted to ruderal weed communities dominated by either R or C–R species, or to woodland-scrub communities dominated by C–S–R and S–C species, depending on proximity to woodland and previous land use [70], with ex-grassland sites close to woodland most likely to develop the possibly more desirable woodland-scrub communities [70]. The communities' types were similar to those reported in other European studies [68,69,71].

Table 2
Plant species recorded in over 25% of 21 UK SRC plantations, surveyed during two survey periods

Species	% Plots in which species was record	
	1993	1996
Urtica dioica	80.6	80.6
Ranunculus repens	55.6	58.3
Cirsium arvense	52.8	58.3
Galium aparine	58.3	47.2
Epilobium montanum	52.8	44.4
Rubus fruticosus	33.3	44.4
Poa trivallis	30.6	44.4
Rumex obtusifolius	52.8	38.9
Poa annua	27.8	36.1
Rumex crispus	27.8	25.0
Cirsium vulgare	36.1	27.8

Adapted from Sage and Tucker [70].

6.1.1. Introduction of wildflowers

It has been suggested that maintaining ground cover of stress-tolerant, slow-growing plant species under SRC crop is preferable to bare ground as it has the potential to reduce erosion risk, act as competition for more competitive weed species, preserve soil moisture, provide habitat for species involved in natural pest control and enhance wildlife and game value of the crop [70,73]. However, the natural colonization by these species is slow. Thus, the feasibility of introducing shade tolerate species to SRC was examined in a three year study, in which 17 woodland species were introduced into SRC willow [70]. All but one species survived, with 10 species increasing percentage cover over the survey period. Thirteen species also flowered leading the authors to suggest that the establishment of shade tolerant plant species to SRC may be feasible [70]. In addition, this type of management may also help to improve the public acceptance of SRC plantations and would also decrease the need for herbicide applications [70].

6.2. SRC and avian diversity and utilization

Avian diversity within SRC plantations has received much attention. This section examines overall effects on biodiversity, the effect of management, utilization of SRC by birds, and SRC as a potential game bird resource.

6.2.1. Overall effects on avian diversity

In general, positive effects on avian biodiversity of SRC within a farmland landscape have been reported [68,69,74,75]. For example, in a UK-based study involving 22 plots of SRC willow, Sage et al. [74] reported increases in avian density and species richness in comparison to both arable and improved grassland controls. With mean spring densities of 3.1 birds ha^{-1} in SRC, 0.8 ha^{-1} in arable land and 1.63 ha^{-1} in improved grassland. The SRC plots also had consistently higher species richness, with up to 19 more species recorded in SRC compared to arable and grassland controls [74]. These results are consistent with those of a Swedish study in which species richness in SRC was found to be higher than either cropland or set-aside [75]. In comparison to SRC willow, SRC poplar appears to support a lower avian abundance and diversity. For example, up to 13.8 breeding songbirds ha^{-1} have been recorded in SRC willow compared to 4.8 ha^{-1} in SRC poplar [72]. However, both type of plantation have been shown to increase species diversity and abundance compared with arable row crops [72].

The most commonly recorded species are those associated with scrub and woodland habitats such as blackbirds (*Turdus merula*), chaffinch (*Fringilla coelebs*), dunnock (*Prunella modularizes*), great tits (*Parus major*), reed bunting (*Emberiza schoeniclus*), willow warbler (*phylloscopus trochilus*) and wren (*Troglodytes troglodytes*). Other species also recorded including seven UK amber listed species (sensu Gregory [76]) and 6 red listed species [68,72,74]. There is however some concern that widespread planting of SRC could displace species that prefer open farmland habitats such as sky larks (*Alauda arvensis*), meadow pipit (*Anthus pratensis*) and lapwing (*Vanellus vanellus*). However, some open farm birds have been recorded in recently harvested SRC, suggesting that including a range of harvest cycles in large plantations could reduce any negative effects [74]. Nevertheless, the rapid growth rate of willow may limit the effectiveness of this method, and a few species such as the yellow wagtail (*Motacilla flava*), grey partridge (*Perdix perdix*) and stone curlew (*Burhinus oedicnemus*), are likely to be negatively affected by establishment of SRC regardless of harvest cycle [68,74].

It is also important to note that while SRC can increase avian diversity compared to arable crops, it represents a poorer habitat than many natural and semi-natural habitats such as ancient woodland, wet meadows and unimproved grassland [68,70].

6.2.2. Management

Management has a marked effect on avian species richness and diversity. Time since last harvest for example influences both species abundance and composition, as illustrated by a study by Coates and Say [69] in which increases in the density of breeding birds and changes in species composition were reported as coppice matured to a maximum of 5 years (Table 3). However to maximum yield SRC is usually harvested every three years, highlighting one potential conflict between management of SRC for biodiversity and economic profit.

Sage et al. [109] also reported that planting density, structural density between 1 and 4 m, and the level of weed-cover are positively related to avian species richness and abundance, suggesting that management practices promoting these factors would enhance avian biodiversity. The importance of the crop area to edge ratio was also highlighted in Cunningham et al. [68], who reported that with increased time since last harvest an edge effect becomes increasingly apparent, with higher species abundance recorded at the edge of plantations compared to the

Table 3
Six most frequently recorded breeding bird species per harvest cycle, recorded during surveys in five farms in southern England (territories ha^{-1}) (from Coates and Say [69])

Establishment year		Year 1		Year 2	
Species	Territories (ha^{-1})	Species	Territories (ha^{-1})	Species	Territories (ha^{-1})
Alectoris rufa	0.06	*Alectoris rufa*	0.07	*Phasianus colchicus*	0.21
Alauda arvensis	0.04	*Alauda arvensis*	0.07	*Acrocephalus scirpaceus*	0.16
Phasianus colchicus	0.02	*Phasianus olchicus*	0.04	*Emberiza schoeniclus*	0.16
Vanellus vanellus	0.02	*Emberiza schoeniclus*	0.04	*Phylloscopus trochilus*	0.14
Motacilla flava	0.02	*Phylloscopus trochilus*	0.03	*Sylvia borin*	0.09
Miliaria calandra	0.02	*Miliaria calandra*	0.01	*Turdus merula*	0.09
Year 3		Year 4		Year 5	
Phylloscopus trochilus	0.40	*Phylloscopus trochilus*	1.04	*Phylloscopus trochilus*	0.97
Acrocephalus schoenobaenus	0.21	*Acrocephalus scirpaceus*	0.38	*Turdus merula*	0.41
Emberiza schoeniclus	0.21	*Emberiza schoeniclus*	0.38	*Acrocephalus scirpaceus*	0.41
Phasianus colchicus	0.19	*Erithacus rubecula*	0.27	*Fringilla coelebs*	0.41
Erithacus rubecula	0.15	*Turdus merula*	0.27	*Phasianus colchicus*	0.28
Acrocephalus scirpaceus	0.11	*Acrocephalus schoenobaenus*	0.22	*Emberiza schoeniclus*	0.28

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interior. Furthermore, the boundary of SRC plantations (i.e. the hedgerows) also support a higher avian diversity and abundance than arable crop boundaries, leading to the suggestion that high crop to edge ratio may benefit avian biodiversity [68]. However the smaller plots sizes or irregular shaped plantations that this would entail, may have negative commercial implication.

Birds have also been shown to prefer certain varieties of willow and poplar for nesting, with studies of preferred varieties suggesting that a lattice like branching nature could be a desirable trait for improving nest site availability within plantations [77].

6.2.3. Utilization

There are questions about how birds actually utilize SRC and their level of dependence upon this crop. One study of passerine breeding territories in part investigated this [70]. The authors reported that of 22 species present in the survey area, pheasant *(Phasianus colchicus*), willow warbler, garden warbler (*Sylvia borin*), sedge warbler (*Acrocephalus schoenobaenus*) and reed bunting appeared to prefer SRC to other habitats available [70]. Only pheasant and reed bunting always incorporated SRC in their territories, while gold crest (*Regulus regulus*), chiffchaff (*Phylloscopus collybita*) and blackcap (*Sylvia atricapilla*) were never recorded in SRC. The remaining species occasionally included SRC in their territories [70], suggesting that the level to which SRC is utilized is species dependant. Nesting success within SRC plantations is also poorly understood, and SRC plantations are unlikely to provide a suitable habitat for cavity nesting species such as tits [78]. Further work on both nesting success and the level to which SRC plantations are utilized by birds for forage and shelter is still required.

6.2.4. Game birds

The economic implication of SRC for game bird management has underpinned several studies on the relationship between SRC use by species such as pheasant and partridge. Sage et al. [72] concluded that SRC is an attractive habitat for pheasants, with individuals recorded in 13 out of 19 sites visited, and a mean male territory density in occupied sites of 2.9 territories km^{-1}, a similar value to the 2.6 territories km^{-1} reported for scrubby woodland edge [72]. Red-legged partridge (*Alectoris rufa*) and grey legged partridge (*P. perdix*) were also recorded in 37% and 16% of the sites, respectively [72]. Baxter et al. [79] investigated both partridge and pheasant use of SRC and suggested that although pheasants seem to prefer willow over poplar, for partridge the opposite is true [79]. Snipe (*Gallinago gallingo*) have also been recorded in SRC. Radio transmitters used to track snipe showed that they roosted in SRC during the day before feeding at night in nearby pasture land [70], leading the authors to suggest that land owners wishing to encourage snipe should consider planting SRC near to suitable feeding areas [70].

6.3. SRC and invertebrate diversity

6.3.1. Canopy invertebrate and Coleoptera diversity and abundance

Owing to the low pesticide inputs in SRC and, particularly in the case of willow, the large number of associated insect species, it is generally expected that SRC will support a diverse range of invertebrates [16,70,80]. Studies on invertebrate diversity within SRC support this assumption. For example, Sage and Tucker [70] recorded 120 invertebrate species or groups of species in the canopy of SRC willow plantations and 70 invertebrate species in SRC poplar plantations. Further analysis of a matched sub-set of sites showed that willow contained both a greater diversity of invertebrates and higher abundance in most groups than in poplar [70]. The most abundant and widespread species were leaf beetles (Coleoptera: *Chrysomelidea* spp.) with a mean density of 7.55 individuals m^{-2} in willow and 11.64 individuals m^{-2} in poplar, with orders Hymenoptera, Hemiptera, Lepidoptera and Arachnidea, also well represented. Cunningham et al. [68] reported similar findings with the addition that Thysanoptera were found to be most abundant in a study of 12 willow plantations. Sage and Tucker [70] identified 30 species of ground beetle (Carabidae) and 15 species of rove beetles (Staphylinidae) using pitfall traps at three sites in north west England, similar numbers to those reported by Coates and Say [69] who recorded a maximum of 27 ground beetles and 25 rove beetles at any one site during pitfall trapping at five SRC sites in southern England. The range of species collected by Sage and Tucker [70] through canopy sampling, pitfall traps and a small number of direct stem searches comprised species from 16 orders (Table 4). No direct comparison to arable row crops was made in these studies. However, it was suggested by Cunningham et al. [68] that as only around 45 species of phytophagus invertebrate utilized cereal crops, SRC should increase invertebrate diversity compared to arable crops [70].

6.3.2. Butterflies

In comparison to arable controls, Cunningham et al. [68] reported that the boundary of SRC willow contained both a higher butterfly abundance and species richness than arable controls [68]. Of the 22 species recorded, none were found exclusively in the SRC, and all were relatively common and widespread species. A finding in line with the study by Sage et al. [72] in which of 14 species of butterflies were recorded in SRC plantations (Table 5) where most were common, migratory or colonial polyphagous species with weed or stress tolerant food plants [72]. This study also showed that headlands contained significantly higher species richness and abundance than either the crop or the rides, with mature crops containing the lowest abundance [72]. The authors therefore suggest that headlands represent a key habitat for butterflies within SRC plantations, and that the additional shelter the crop provides could

Table 4
Orders and classes of invertebrates collected in UK SRC plantations

Orders	Number species	
	12 Plots SRC willow	9 Plots SCR poplar
Coleoptera	30	
Hymenoptera	21	11
Hemiptera	18	14
Diptera	14	6
Lepidoptera	12	
Trichoptera	2	16
Neuroptera	3	
Psocoptera	1	1
Orthoptera	1	1
Dermaptera	1	1
Mecoptera	1	
Isopoda	1	1
Classes		
Diplopoda		1
Chilopoda		1
Gastropods	2	3
Arachnida	12	
Pit falls Traps (*SRC willow and poplar*)		
Coleoptera	45	

Adapted from Sage and Tucker [70].

Table 5
Mean number of Lepidoptera species km^{-1}, recorded in 50 m transects over 16 sites of SRC plantations in UK

Species	Uncut crop	Cut crop	Headlands	Rides
Maniola jurtina	0.00	2.36	3.78	1.12
Aphantopus hyperantus	0.22	0.40	3.38	0.00
Pyronia tithonus	0.22	1.56	2.44	1.12
Aglais urticae	0.00	1.56	2.16	2.22
Artogeia rapae	0.22	1.56	2.02	0.00
Ochlodes venata	0.44	0.40	1.36	0.00
Pieris brassicae	0.22	0.40	1.36	0.00
Thymelicus sylvestris	0.00	1.18	0.12	1.12
Anthocharis cardamines	0.00	0.78	0.94	0.00
Pieris napi	0.00	0.00	0.94	0.00
Vanessa atalanta	0.22	0.00	0.28	1.12
Pararge aegeria	0.00	0.00	0.28	0.00
Polygonia c-album	0.00	0.00	0.14	0.00
Euphydryas aurinia	0.00	0.00	0.14	0.00

Adapted from Sage et al. [72].
Uncut, refers to sample of 89 transect within mature unharvested crop, cut-crop, refers to 51 transects within recently harvested crop, Headlands refers 148 transect within the uncultivated area at the field margins, Rides, refer 18 transects within uncultivated strips running through the crop.

account for the difference between the plantation and arable headlands [72].

6.3.3. *Flower visiting insects*

Redderson [81] investigated the level of resources provided for flower visiting insect species by SRC willow and its associated ground flora [81]. The study concluded that while ground flora represents a poor source of nectar due to both the species present and the limited flowering under a mature crop canopy, flowering of the willow stools in the 2nd and 3rd years of growth may constitute an important early season source of nectar and pollen for flower visiting insects such as bees [81].

6.3.4. *Soil invertebrates*

Reduced soil tillage, pesticide inputs and increased litter of SRC might be expected to be beneficial for soil invertebrates. However, remarkably few studies have investigated the effect of SRC plantations on either euedaphic or hemiedaphic species of soil invertebrates. In Germany increases in abundance and mass of earthworm, woodlice and harvestmen under SRC compared to adjacent arable fields were observed [39]. However, Coates and Say [69], in a study of five sites of SRC in southern England, found that earthworm numbers decreased over the 6 years of the study. This is clearly an area where more research is required, especially as soil invertebrates play important roles in ecosystem function and nutrient cycling [82].

6.4. *Mammals, amphibians and reptiles*

The use of SRC by mammals, amphibians and reptiles has also so far received little attention. Coates and Say [69] carried out small mammal trapping and an informal survey of mammals present in five SRC sites, including the use of a bat detector at one site. The small mammal trapping suggested that SRC provided a more attractive habitat for small mammals than arable land, with older coppice being most attractive, nevertheless it still represents a poorer habitat than hedgerow and scrub land [69]. Sage and Tucker [70] also recorded mammal species seen during their four-year study of 21 sites of SRC in England. Species observed in SRC plantations included 17 mammals, three amphibians and a single sighting of a grass snake (Table 6) [69,70]. In Sweden, Bergstrom and Guillet [83] monitored

Table 6
Mammal species record in SRC plantations within the UK

Species recorded in SRC plantations

Meles meles
Vulpes vulpes
Capreolus capreolus
Mustela erminea
Oryctolagus cuniculus
Lepus capensis
Talpa europaea,
Eptesicus serotinus
Pipistrellus pipistrellus (45 kHz)
Pipistrellus pipistrellus (55 kHz)
Erinaceus europaeus
Apodemus sylvaticus
Sorex minutus
Microtus agrestis/ *Clethrionomys glareolus*
Sorex araneus
Micromys minutus
Rattus norvegicus
Natrix natrix
Rana temporaria
Bufo bufo
Triturus cristatus

Adapted from Sage et al. [70] and Coates and Say [69].

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summer browsing of SRC willow by large herbivores such as rabbit, deer and moose. They reported that all of the 15 willow plantations surveyed had been browsed, with browsing pressure highest in the first year [83]. The authors suggest that although large herbivores such as deer and rabbit are often considered pest of SRC plantations, SRC willow could also be viewed as a resource for deer and moose in terms of the game value of these species [83]. The economic benefit of increased cover for large game however could be offset by the level of economic damage these large herbivores would cause.

6.5. *Miscanthus and biodiversity*

Our understanding of the potential effects of perennial grasses like Miscanthus on biodiversity is limited in the UK to a single three-year study involving two plantations of Miscanthus, and two of reed canary grass [84]. Poor establishment of Miscanthus in this study makes conclusions difficult, although the successful establishment of the reed canary grass may provide an insight to how Miscanthus plantations may develop [84].

Twenty-five plant species were recorded from within the grass crops, and 48 from headlands [84]. Flora diversity and percentage cover were also higher in the plantation than within the arable controls. However, during the course of the study the percentage cover in the reed canary grass dropped dramatically from 48% in first establishment year to 1% in the final year, a level comparable to adjacent arable crops [84]. Avian diversity within reed canary grass plantations was also lower than within the Miscanthus, with a maximum of eight species recorded compared to 19 species within the Miscanthus. Numbers in the headlands were greater, although in comparison to values for SRC [74], it appears that Miscanthus will not be as beneficial to avian diversity as SRC.

Invertebrate surveys were conducted within the plantation using walked transects or sweep netting [84]. In total, 15 species of butterfly, four species of bumble bees and 10 species of hoverflies were recorded in the perennial grass plantations during the transect surveys [84]. Headlands generally had the highest diversity and abundance, and no species of bumble bee or hoverfly were recorded in cropped areas of the reed canary grass plantations [84]. The arboreal insect diversity in reed canary grass plots was also lower than that of the Miscanthus plantations, leading the authors to suggest that as Miscanthus matures diversity may decline within the cropped area [84].

These initial results would suggest that Miscanthus plantations may not support as many species as SRC plantations, however the limited amount of research makes the possible effects of this crop on farmland biodiversity difficult to predict. Clearly, this is an area where further research is urgently required, and should become easier as the number of these plantations within the UK increases.

7. Impacts of SRC and Miscanthus on hydrology

It is generally expected that Miscanthus and SRC will have higher water demands than arable crops due to a combination of higher growth rates, high transpiration rates, longer seasonal growth and increased rooting depth and complexity [85,86]. Indeed one UK field study concluded that transpiration rates in SRC willow and poplar are higher than both agricultural crops and other tree crops currently grown in the UK [87]. However, it should be noted that this study was undertaken on a limited number of genotypes known to have a high water use [87]. Peak transpiration rates of 8–10 mm day^{-1} and an yearly averages of 6 mm day^{-1} were recorded despite a period of unusually dry weather when transpiration rates fell dramatically [87]. Transpiration rates for Miscanthus are generally expected to be lower than those of SRC, given that Miscanthus has C4 photosynthesis. In a study of water loss from un-irrigated and irrigated Miscanthus crops, water loss was lower than in SRC, averaging 2.3 and 3.4 mm day^{-1} from the unirrigated and irrigated crops, respectively, with a peak value of just 5 mm day^{-1} [88]. On the larger scale, for example, Stephens et al. [85] modelled the potential hydrological impacts of SRC and Miscanthus at the catchment scale in four areas of the UK (Cambridge, Selby, Diss and Cirencester) where the use of biomass for power generation was expected to occur. In all cases, predicted mean annual evapotranspiration of both Miscanthus and SRC willow were higher than either permanent grassland or winter wheat. An example for Selby is shown in Table 7 [85]. Stephens et al. [85] model also analysed the effects on hydrologically effective rainfall HER (sum of runoff and deep percolation), predicting that the combined effect of increased transpiration rate together with increases in interception losses will lead to decrease in HER of 50–60% for Miscanthus and 75–90% for SRC willow over the four location [85]. The authors concluded that this reduction is in part due to the increased rooting depth of these crops, which allows them to dry soil up to a depth of 2–3 m, therefore requiring more rainfall to replace this loss before percolation will occur [85]. At the catchment scale, the authors conclude that provided plantations are not concentrated in one small area, the establishment of energy crops within the suggested 40 km radius of individual power stations is unlikely to have

Table 7
Predicted water loss through transpiration for four different land uses in Selby, Yorkshire, UK data from Stephens et al. [85]

Land use	Predicted annual transpiration (mm)
Permanent grass land	410
Winter Wheat	411
Miscanthus	427
SRC	462

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a noticeable effect on base flow since the overall land area devoted to these crops will be small [85]. The authors of the Government guidelines for growing SRC came to similar conclusions, with the additional constraint of requiring the plantations to be located in areas where annual rainfall is at least 600 mm year^{-1} [89]. They also concluded that catchment scale effects of SRC plantation on hydrology would be negligible, provided extensive areas of single catchments are not planted [89]. The authors warn that the average precipitation over the growing season for production of 12 ODT ha^{-1} year^{-1} in SRC plantations is around 550 mm (Fig. 3) and thus planting in areas with significantly lower rainfall will result in reduced production unless additional water could be supplied [89]. The authors also suggest that planting riparian strips of SRC will have little effect on most river and streams as abstraction rates of plantations are general low, however in small streams, headwater stream and areas upstream from wetlands the effects could be more dramatic and thus it is advisable to avoid planting in these areas [89]. Guidelines produced for Miscanthus follow the same general advice, although the lower predicted annual transpiration rates for Miscanthus of between 40 and 100 mm (Fig. 3) leads the authors to suggest that these crops may be more suitable than SRC for dry regions such as East Anglia in the UK [90]. It has also been purposed that rather than representing a problem, in some areas the high water use of these energy crops could be utilized in flood management, with the combined effect of soil drying, decreased runoff and increase penetration associated with the establishment of these plantations helping to reduce flooding in at risk areas [55,89,90].

8. Energy and carbon balance

The two aspects which must be considered when assessing the contribution biomass and biofuels have on our ability to meet future energy demands with limited environmental impact are (1) the amount of energy that is required to produce each unit of renewable energy and (2) the greenhouse gas (GHG) emissions that are released in the process. The current evidence base for the use of different feedstock and conversion in terms of these aspects is discussed.

Comparison of the carbon footprint associated with a wide variety of crop types suitable for energy uses in the context of inputs of chemicals and fertilisers, and the use of subsequent co-products has not been undertaken in a systematic way (see Farrell et al. [91] for further discussion).

8.1. SRC and Miscanthus for power generation

Various models have estimated the GHG emission and energy ratio of SRC and Miscanthus both for production only (to farm gate) and including both production and utilization (Table 8). Variation in the figures reflects differences in the model boundaries and assumptions made regarding management practices, crop yields and method of processing. It highlights the need for a consistent framework for such measurements, as advocated by IEA [92,93], since this is a highly contentious area where policy on sustainability and certification must be developed. For example, Heller et al. [94] predicted lower values for both GHG emission and energy ratio for SRC willow than

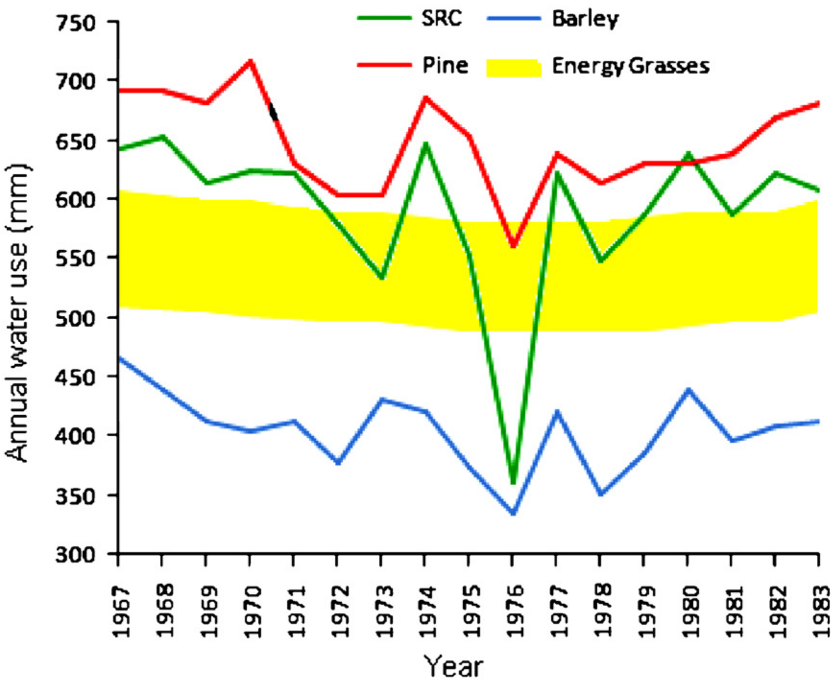

Fig. 3. Predicted water use of SRC and Miscanthus on a clay soil site with annual rainfall of about 700 mm, including inception losses (adapted from Hall [90]).

Table 8
GHG emission and energy ratio of biomass production and production plus utilization, for SRC and bioenergy grass crops

Fuel source	GHG emissions (g C eq. (MJ^{-1}) of biomass	Energy ratio MJ$_{produced}$/MJ$_{input}$	Author
SRC willow	0.19[a]	11[a]	Heller et al. [94]
SRC willow	1.7–2.7[a]	17–20[a]	Dubuisson and Sintzoff [95]
SRC willow and poplar	1.3[a]	28.68[a]	Matthews [47]
SRC willow		21[a]	Börjesson [98]
Reed canary grass		11[a]	
SRC willow	1.36[a]		Lundborg as cited in Boman and Turnbull [100]
Miscanthus	0.512[a]	35.86[a]	Bullard and Metcalfe [97]
Switchgrass	0.629[a]	28.97[a]	
Reed canary grass	0.89[a]	20.4[a]	
SRC willow	0.13[b]	13[b] 55[c]	Keoleian and Volk [104]
CHP (small scale) gasification SRC	1.23[d]	10.34[d]	Adapted from Elsayed et al. [96]
Electricity from gasification SRC	2.04[d]	6.21[d]	
Electricity from pyrolysis SRC	4.13[d]	3.11[d]	
Electricity form combustion SRC	6.54[d]	2.73[d]	
Electricity (large scale) Miscanthus	7.09[d]	3.68[d]	

[a] Values for harvested crops (chipped or baled).
[b] Values for production and gasification of willow of power generation.
[c] Values for willow at farm gate.
[d] Values for production and utilization for power generation.

Dubuisson and Sintzoff [95] (Table 8). Unlike Heller et al. [94], Dubuisson and Sintzoff [95] did not include carbon sequestration in the form of SOM but did consider additional crop maintenance and harvest practices such as electric fencing and force drying. These examples emphasize how results depend greatly on how accurately the models fit the current conditions. Nevertheless, these models do provide a very powerful tool for assessing the impacts of each stage of biomass production, and variation between crop types and processing methods. There is general agreement that in the case of SRC the use of inorganic nitrogen fertiliser has a significant effect on the carbon balance and energy balance of the crop, accounting for up to 37% of the fossil energy input [94–96]. This could be dramatically reduced if waste water and sludge are used as alternative fertilisers [95]. Heller et al. [94] also suggest that improved efficiency in the chipping process would significantly reduce GHG emissions.

Fewer models have been constructed for the production of Miscanthus, however Bullard and Metcalfe [97] concluded that inputs of pesticides, fertiliser and harvesting have the strongest negative impact on GHG emission and energy balance for this crop, while the energy ratio is most sensitive to changes in yield. The authors also suggest that energy grasses have a higher energy ratio and lower GHG emission than SRC [97], however models by Börjesson [98], Elsayed et al. [96] and Smith [99] all refute this point.

Analysis of contrasting power production routes by Elsayed et al. [96] suggests that the utilization of SRC in CHP plants provides the best option for reduced carbon emission and maximal energy ratio. The most important message is that in comparison to fossil fuels (Table 9) all models predict that both SRC and Miscanthus provide clear carbon savings.

Table 9
Greenhouse gas emission from production and combustion of fossil fuels, for comparison to figures for bioenergy production

Fuel source	GHG emissions: (g C eq. (MJ^{-1})	Energy ratio (MJ$_{produced}$/ MJ$_{input}$)	Author
Coal	29.1		Matthews [47]
Coke	31.8		
Fuel oil	22.1		
Diesel oil	21.1		
LPG	20.0		
Natural gas	18.0		
Coal	30.02		Gustavsson et al. [105]
Coke	36.42		
Gasoline	23. 07		
Diesel	22.24		
Fuel oil	22.10		
LPG	21.96		
Natural gas	18.63		
Diesel	87	0.79	Elsayed et al. [96]
Petrol	81	0.84	
Fuel oil	87	0.84	
Electricty	162	0.32	
CHP	101	0.72	
Heat from oil powered boiler	105	0.69	

8.2. Biofuels production

GHG emission and energy ratios of liquid biofuel production are generally less favourable than those reported for biomass heat and power production (Tables 8 and 10). Biodiesel and bioethanol still represent a significant reduction in GHG emissions [98,100,101] compared to oil.Kim and Dale [101] predict that within the USA the production of bioethanol from maize starch can result in GHG emission reductions for a family car of between 41 and 61% km^{-1} driven compared to fossil fuel sources. For GHG emission and energy inputs during the processing of bioethanol, the model by Mortimer et al. [102] suggests that the processing and, in particular, the hydrolysis, fermentation and distillation of wheat grain and sugar beet are the most energy demanding stages and release the highest percentage of GHG. Overall the processing of wheat grain and sugar beet accounts for 57% and 67% of the GHG emission, and 64% and 74% of the energy inputs, respectively [102]. Fertiliser application in both wheat and sugar beet also contribute a large fraction of the GHG emission, accounting for 16% and 19% of the overall emissions for the wheat and sugar beet, respectively [102]. Mortimer et al. [102] suggested that the energy balance of these crops could be further improved by using waste straw as a fuel source, as GHG emission and energy inputs for straw production are effectively zero since they are by-products of wheat grain production.

9. Conclusion and recommendations

The use of dedicated, second-generation biomass crops for the supply of power and liquid transportation biofuel has the potential to provide a range of benefits for both ecosystem services and carbon mitigation compared with the use of land for arable crop production and, to some

Table 10
GHG emission and energy ratios of the production of bioethanol and biodiesel

Fuel type/source/energy source used for production	GHG emissions (g C eq. (MJ^{-1}) of biomass	Energy ratio (MJ$_{produced}$/MJ$_{input}$)	Author
Sugar beet		12[a]	Powlson et al. [106]
Wheat		7.2[a]	
Oil seed rape		4.49[a]	
Bioethanol/maize	2.64–9.38	1.2–1.9	Seungdo and Dale [101]
Ethanol/grain/fossil fuel	23.18		Lundborg as cited in Boman and Turnbull [100]
Ethanol/forest residues/waste heat	1.64		
Biodiesel/oil seed rape	4.09		
Biodiesel/oil seed rape	11.18	2.29	Elsayed et al. [96]
Ethanol/wheat straw	3.54	−35.71 (4.1)[a]	
Ethanol/sugar beet	10.91	2.02	
Ethanol/wheat	7.91	2.16	
Ethanol/maize	2.08[e]	1.25	Hill et al. [107]
Biodiesel/soya bean	1.75[e]	1.25[d]	
		1.93	
		3.67[d]	
Ethanol/corn	20.99–24.81	1.30–1.06	Farrell et al. [91]
Ethanol/cellulosic	2.99	10	
Ethanol/wheat/natural gas and grid electricity	11.99	1.55	Mortimer et al. [102]
Bioethanol/wheat/natural gas CHP with steam turbine	11.99	1.67	
Bioethanol/wheat/natural gas CHP with gas turbine.	8.99	2.47	
Bioethanol/wheat/straw fired CHP, with steam turbine	3.82	−14.28 (2.41)[b]	
Bioethanol/sugar beet/natural gas and grid electricity	12.81	1.21	
Bioethanol/sugar beet/natural gas CHP with steam turbine	10.63	1.47	
Bioethanol/sugar beet/natural gas CHP with gas turbine	5.99	2.78	
Bioethanol/sugar beet/straw fired CHP, with steam turbine	−29.72 (8.45)[b]	−1.92 (2.64)[c]	

[a] Excluding credit for electricity and acetic acid production from by products.
[b] Excluding credit for electricity exported to grid.
[c] Excluding credit for exported electricity and lime.
[d] Including credit for co-product production.
[e] Calculation for GHG emission refer only to cultivation only, energy ratio is however a fully LCA for field to pump.

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Table 11
Summary of recommendations purposed in the reviewed literature, to minimize the impact and maximize the environmental and economic benefits of biomass crops

Factor	SRC	Miscanthus	Liquid biofuel crops from starch and oil
Soil condition	To maximize carbon sequestration and minimize nitrogen leaching, locate plantation in areas with low soil organic carbon and nitrogen levels [41]	To maximize carbon sequestration and minimize nitrogen leaching, locate plantation in areas with low soil organic carbon and nitrogen levels [41].	
	Consider using SRC as riparian buffer strips to reduce sediment and nitrate loading of waterways [37,49]	To maximize economic and environmental benefits, use waste water and sludge's for fertilization	
	Where possible, use SRC for treatment of contaminated land, landfill leachate, waste water and sludge's		
Biodiversity	Avoid sites with high wildlife value [69,70,72]	Avoid sites with high wildlife value[d]	Consider growing both winter and spring varieties of oilseed rape to extended flowering season [108]
	Design plantations with large edge to interior ratio and incorporate rides and headland of at least 6 m in width [69,68,72]	Intersperse blocks with other farmed habitats[d]	Restrict size of crop and do not grow set aside rape next to commercial rape [108]
	Intersperse blocks of SRC with other farmed habitats and keep plots size below 15 ha [72]	Limit use of herbicides[d]	In large crop consider leaving wildlife corridors [108]
	In large plantations incorporate plots with varying harvest cycles [69,70,72]	Introduce nectar sources to rides and headlands[d]	Avoid varieties with unpalatable seeds such as HEAR [108]
	Use a mix of varieties [69,70]	Maintain a low level of disturbance on headlands and rides to provide habitat suitable for declining arable weed[d]	Follow good agronomic practice, keeping pesticide application to minimum [108].
	Limit the use of herbicides [70,72]		Allow the crop to ripen naturally to prolong bird nesting time, if desiccation is require spray rather than swath the crop [108]
	Plant near existing woodland habitat, and use plantations to link areas of existing woodlands [68,70,72]		Only use bee friendly sprays [108].
	Encourage the growth of native slow growing shade tolerant plant species in crop [68,69,72].		Sow headlands with wild bird cover, to act as wildlife corridors [108]
	Introduce nectar sources to rides and headlands [72].		If set aside land is to be used leave 10% as wildlife corridors with wild bird cover [108].
	Use willow clones with range of flowering times [81]		
	Maintain a low level of disturbance on headlands and rides to provide habitat suitable for declining arable weed [69]		
	Use willow rather than poplar and select "bushy" clones [72,77][a]		
	Increase low shrub cover at edge of plot [70,72][a]		
Hydrology	Plant SRC only where annual rainfall is greater than 300 mm, and preferable at least 550 mm [89][b]	In dry areas use Miscanthus or other energy grasses in preference to SRC [90][b]	
	In large plantations incorporate plots with varying harvest cycles to stager timing of maximum water use by individual plots [89][c]	The drying of the soil profile by energy grass such as Miscanthus may be used to reduce risk of local flooding [90]	
	In terms of large scale planting needed for supply of power station, spread individual plantations across supply area [85,89][c]		
	Avoid sensitive areas, such as near small streams and wetland areas [85,89][c]		
	Plant new varieties with higher water use efficiency when they become available [85,89][c]		

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Table 11 (*continued*)

Factor	SRC	Miscanthus	Liquid biofuel crops from starch and oil
	Plant large blocks to limit increased transpiration at edges [85,89][c]		
Energy and carbon balance	Replace inorganic fertilisers with sewage sludge and waste water [94,95]	Replace inorganic fertilisers with sewage sludge and waste water [97]	Use non-till methods where possible [101]
	Minimize distance between plantation and power plants [95]	Minimize distance between plantation and power plants [95]	Utilities high starch content wheat cultivars when they become available [98]
	Develop local CHP station [96]	Develop local CHP station [96]	Use biomass fuel sources to provide energy for processing [102]

[a] Biodiversity recommendations designed specifically to benefit avian species.

[b] Hydrological recommendation designed to maximize yield.

[c] Whilst thoses designed to minimize impact on local hydrology.

[d] No specific recommendation for Miscanthus have be published however it is likely that these recommendation original suggested for SRC would apply equal to Miscanthus.

extent, set-aside. Fewer benefits are apparent when deployment of bioenergy crops is used to replace permanent unimproved grassland. It is also clear that although SRC and Miscanthus plantations could be generally regarded as beneficial for biodiversity in an agricultural setting, they are not a substitute for natural and semi-natural habitats. Key to success with these crops is the careful siting of plantations, effective management plans and development of efficient processing methods, particularly for liquid biofuels. A summary of the recommended practices for SCR, Miscanthus and biofuel crop production suggested in the literature is given in Table 11.

9.1. The future of energy crops

Bioenergy crops are set to increase in the UK and wider landscape. To develop a sustainable biomass market the aim must be to make biomass economically viable, by a combination of increases in yield and efficient processing methods. In the case of Miscanthus and SRC–increases in the crop value are likely to result in increases in the number of plantations and more intensive management especially for weed control, which is currently not viewed as economically viable. This could lead to both positive and negative outcome for soil condition the impacts are likely to remain positive especially if crop area is increased. Moreover, increased use of these crops for phytoremedation and the treatment of waste water and sludge's has the potential to assist in making these crops economically viable, but further research including genotype screening is required to supply new elite varieties that provide good biomass yield while offering specific phytoremediation specialities [59,60,67].

The effects of more intensive management on biodiversity are likely to be negative, although the inherit wildlife benefit of the crops especially SRC willow means that these crops have the potential to continue to provide a valuable wildlife habitat if placed in agriculturally dominated landscapes. For carbon mitigation, the development of improved processing methods particular in the case of liquid biofuels will be critical if the maximum benefits possible are to be achieved.

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