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Mitigation potential and environmental impact of centralized versus distributed BECCS with domestic biomass production in Great Britain

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Abstract

New contingency policy plans are expected to be published by the United Kingdom government to set out urgent actions, such as carbon capture and storage, greenhouse gas removal and the use of sustainable bioenergy to meet the greenhouse gas reduction targets of the 4th and 5th Carbon Budgets. In this study, we identify two plausible bioenergy production pathways for bioenergy with carbon capture and storage (BECCS) based on centralized and distributed energy systems to show what BECCS could look like if deployed by 2050 in Great Britain. The extent of agricultural land available to sustainably produce biomass feedstock in the centralized and distributed energy systems is about 0.39 and 0.5 Mha, providing approximately 5.7 and 7.3 Mt_{DM}/year of biomass respectively. If this land-use change occurred, bioenergy crops would contribute to reduced agricultural soil GHG emission by 9 and 11 Mt_{CO_2eq}/year in the centralized and distributed energy systems respectively. In addition, bioenergy crops can contribute to reduce agricultural soil ammonia emissions and water pollution from soil nitrate leaching, and to increase soil organic carbon stocks. The technical mitigation potentials from BECCS lead to projected CO_2 reductions of approximately 18 and 23 Mt_{CO_2}/year from the centralized and distributed energy systems respectively. This suggests that the domestic supply of sustainable biomass would not allow the emission reduction target of 50 Mt_{CO_2}/year from BECCS to be met. To meet that target, it would be necessary to produce solid biomass from forest systems on 0.59 or 0.49 Mha, or alternatively to import 8 or 6.6 Mt_{DM}/year of biomass for the centralized and distributed energy system respectively. The spatially explicit results of this study can serve to identify the regional differences in the potential capture of CO_2 from BECCS, providing the basis for the development of onshore CO_2 transport infrastructures.

KEYWORDS

agricultural GHG emissions, BECCS, bioenergy crops, carbon capture and storage, climate mitigation strategy, future energy scenarios, greenhouse gases, land-use change

1 | INTRODUCTION

In recent years, international agreements under the United Nations Framework Convention on Climate Change such as the Paris Agreement have encouraged the development of initiatives that stimulate greenhouse gas (GHG) removal (GGR) methods and carbon (C) trading markets (GGR, 2018). In 2017, the total United Kingdom GHG emissions were provisionally 43% lower than in 1990 (BEIS, 2017). Three quarters of these emission reductions have been ascribed to the reduced burning of coal for electricity generation, and the progressive introduction of bioenergy and alternative renewable energy sources in the energy mix (BEIS, 2017; DECC, 2015a, 2015b). The end of coal burning for power generation, planned for the year 2025, however, represents only a limited improvement towards the United Kingdom's long-term emission reduction targets of 80% by 2050 (Committee on Climate Change, 2017). In that respect, despite the reduction in emissions made in the power sector, the United Kingdom is currently facing gaps of 146 and 247 million tonnes (Mt) of CO_2-equivalent (CO_{2eq}) in meeting the 4th and 5th Carbon Budgets respectively (Turk et al., 2018).

New contingency policy plans are expected to be published by the UK government to provide plausible routes to keep the power sector on track to 2030, and towards a fully decarbonized energy system by 2050 (Committee on Climate Change, 2017). Among the decarbonizing strategies that will require new stimulus, there is the large-scale deployment of sustainable GGRs such as second-generation bioenergy crops in conjunction with carbon capture and storage (CCS). If deployed at large scale, bioenergy with carbon capture and storage (BECCS) is one negative emission technology (NET) able to remove carbon dioxide (CO_2) from the atmosphere (Smith et al., 2016), as well as the most cost-effective strategy to deliver half of the UK emission targets in 2050 (ETI, 2016). Bioenergy crops such as *Miscanthus*, short rotation coppice (SRC) willow and poplar and short rotation forestry (SRF) have been reported to provide higher biomass yields (Clifton-Brown et al., 2017; Hastings et al., 2014), more favourable energy output/input (Sims, Hastings, Schlamadinger, Taylor, & Smith, 2006) and lower production costs than biofuels produced from conventional food crops (Chum et al., 2011; Hastings, 2017; McCalmont et al., 2017). In addition, depending on the land-use change (LUC) transition and nature of the feedstock, several studies showed significant GHG emission savings, soil carbon sequestration potentials (Hastings et al., 2014; Richards et al., 2017) and ecosystem service benefits such as flood protection, pest control, positive effects on water and soil quality and wildlife game cover (Milner et al., 2016). The large-scale deployment of BECCS, however, involves a number of environmental, economic and social implementation challenges associated with the emissions from LUC to grow bioenergy crops, potential conflicts with food and feed production when bioenergy crops are grown on agricultural land and the building of BECCS infrastructure required for energy vectors that still rely on a fossil fuel supply chain (Fajardy & Mac Dowell, 2017; Hastings, 2017; Samsatli, Samsatli, & Shah, 2015).

Under future technological growth and trade openness, it is reasonable to expect further growth in the supply and demand of domestic bioenergy crops for energy generation as well as a lower price volatility and less risk averse conditions for the UK farmers investing in bioenergy crops (Andrée, Diogo, & Koomen, 2017; van Meijl et al., 2018). In more favourable market conditions, the sustainable cultivation of bioenergy crops on poor quality agricultural lands could represent a portfolio diversification for farmers (Hastings, 2017), and at large scale, an important GGR strategy to enhance the contribution of the agricultural sector in reducing national GHG emissions (Smith et al., 2016). In this study, we investigate the climate mitigation potential of BECCS in Great Britain (GB) with reference to its binding commitment to reduce emissions by 2050. We began by identifying plausible scenarios around the ambition of maximizing the decarbonization of the energy sector to achieve net-zero GHG emissions by 2050 (Greenhouse Gas Removal, 2018). We project two alternative bioenergy production pathways for BECCS based on: (a) a centralized energy system (CES) of large-scale biomass power stations located where existing power plants and industrial sites are currently found and (b) a distributed energy system (DES) of combined heat and power (CHP) stations distributed to meet the heat and power demands in 2050 (DES). Since coal will be phased out of the GB energy mix by 2050, we do not consider cofiring of biomass with fossil fuels.

We assess the technically plausible extent of land available to produce an environmentally and economically sustainable supply of bioenergy crops to CES and DES. We define the technical land for bioenergy crops as the local biomass catchment areas for the power stations, including medium, poor and very poor quality agricultural land to avoid conflicts with food crop production. We project spatially explicit yields for the best performing bioenergy crop types and determine the likely technical potential of domestic biomass supply for the bioenergy sector across GB. Next, we project emissions attributable to bioenergy crop production and energy generation from the combustion of biomass in the power stations. We, therefore, quantify not only the main biophysical processes affected by LUC to bioenergy crop production but also the technical mitigation potentials from CCS, based on the combustion of domestic biomass and capture CO_2 from the power stations in CES and DES. We report the overall climate mitigation potential of bioenergy crops as net GHG exchange from both direct and indirect emissions in LUC estimated over a 35-year time horizon (nominally from 2015 to 2050). We also quantify indicators of environmental impact of bioenergy crops for air, soil and water quality, respectively, through assessing impacts on ammonia emissions, change in soil organic matter content and nitrate leaching.

2 | MATERIALS AND METHODS

2.1 | BECCS pathway scenarios

Two alternative bioenergy pathway scenarios were developed across GB, based on (a) large-scale power plants committed to generate electricity from sustainable biomass (hereafter named CES) and (b) biomass-fuelled CHP stations located at or near the point of energy consumption (DES). Using information on annual CO_2 emissions from existing GB power plants (available at http://naei.beis.gov.uk/reports), CES was based on existing power stations with annual CO_2 emissions ≥10,000 $t_{CO_2\text{-}C}$/year (i.e. 37,000 t_{CO_2}/year), and corresponded to a scenario where fossil fuels are replaced by bioenergy by 2050.

The location of the CHP stations in DES was based on the assumption that these would be installed primarily to meet local nondomestic (i.e. commercial and industrial) heat demands, which is expected to be characterized by higher and more stable annual thermal loads than domestic heat demands in 2050. The spatial information on energy demands for the year 2050 was derived from the 1 km map of domestic and nondomestic heat and nonheating electricity demand across GB based on the 'Additional Policies' scenario reported in Taylor et al. (2014). The location of CHP stations was then based on nondomestic annual heat demand densities above ≥3,000 kilowatt per square km (kW/km^2), which corresponds to a heat demand threshold for developing district heating networks at financial returns of 6%, and greater than the discount rate applied to the public sector (Davies & Wood, 2009). The centroid of the energy demand areas, formed by the above heat demand density, corresponded to the approximate location of the CHP across GB. However, where domestic heat demands are projected, CHP stations maybe required to satisfy the heat demands from both domestic and nondomestic end users, leading to an overall increase in CHP energy requirements. Therefore, the calculation of the biomass demand from the CHP stations included energy requirements from both domestic and nondomestic heat demands. For consistency and ease of comparison, in both the CES and DES, the biomass supplied to the power plants was assumed to be sourced within a catchment area of 40 km radius (5,024 sq. km), which is assumed to be a viable distance to supply biomass to local power stations (Hastings, 2017; Thomas, Bond, & Hiscock, 2013).

2.2 | Land cover and bioenergy crop production

The spatial analysis on GHG exchange from LUC across GB was carried out using the land cover information on agricultural land from Land Cover Map 2007 (LCM2007, Centre for Ecology & Hydrology). More specifically, we used the 100 m resolution raster grid of LCM2007 to aggregate into two broad categories, arable land and grassland (Figure S1a,b), and transformed these into vector data in ArcGIS 10.6 to derive the area of arable and grassland at 1 km resolution.

The bioenergy crop scenario was derived from Hastings et al. (2014), and based on mean annual biomass peak yields (t_{DM} ha^{-1} $year^{-1}$) for the year 2050. This corresponded to the best performing bioenergy crop types grown across GB. In particular, we used the 100 m resolution raster grid of *Miscanthus*, SRC (represented by willow and poplar) and SRF (represented by poplar, aspen (*Populus tremula* L.), black alder (*Alnus glutinosa* L.), European ash (*Fraxinus excelsior* L.), sitka spruce (*Picea sitchensis* [Nong.] Carr.) and silver birch (*Betula pendula* Roth)) simulated by the models MiscanFor (Hastings, Clifton-Brown, Wattenbach, Mitchell, & Smith, 2009), ForestGrowth-SRC (Tallis et al., 2013) and ESC-CARBINE (Pyatt, Ray, & Fletcher, 2001; Thompson & Matthews, 1989), respectively. Simulations were performed using the medium climate change scenario UKCP-09 (equivalent to the latest RCP 6.5 scenario, Intergovernmental Panel on Climate Change [IPCC], 2014; Figure S2a,b). For the GHG emission from LUC, the above bioenergy crop spatial information was transformed to 1 km resolution.

The land availability for arable, grassland and bioenergy crops was based on the UKERC 9w land-use constraints mask reported in Lovett et al. (2014). We considered only the land with slope <15% and corresponding to agricultural land classification (ALC) of grades 3, 4 and 5 (Lovett et al., 2014). We excluded the most productive agricultural land (ALC 1 and 2), woodland, peatland (i.e. soil C ≥ 30%), natural and designated heritage sites, urban areas, rivers and lakes. In addition, within the above land constraint mask, we considered only the locations where the annual yields from bioenergy crops are ≥9 t_{DM}/ha to add an economic limit constraint (Lovett et al., 2009; Richter, Riche, Dailey, Gezan, & Powlson, 2008; Thomas et al., 2013). We assumed that the LUC on marginal agricultural land (i.e. ALC 4 and 5) will largely avoid indirect LUC effects (iLUC; Milner et al., 2016) from bioenergy crop production, providing the extent of land to produce biomass feedstock in an environmentally and economically sustainable manner (hereafter named the sustainable LUC scenario). However, by also including grade 3 land in a separate scenario, we attempt to identify the technically plausible domestic LUC scenario around the ambition of maximizing BECCS in GB, and to achieve the BECCS mitigation target of 50 Mt_{CO_2}/year by 2050 (hereafter named as maximizing scenario).

2.3 | Biomass feedstock demand

The calculation of the biomass demand from CES was based on the energy capacity of the existing power stations with annual CO_2 emissions ≥10,000 $t_{CO_2\text{-}C}$/year. The calculation of the biomass demand from DES was based on the local energy requirements from both domestic and nondomestic electricity and heat demands.

The biomass demand from the power stations in CES was calculated using Equations (1) and (2).

$$\mathrm{EI}_{\mathrm{PS}} = \left(E_{\mathrm{cap}} \times U_{\mathrm{CES}} \times E_{\mathrm{CES}}\right)\left(1 - E_{\mathrm{loss}}\right) \quad (1)$$

where $\mathrm{EI}_{\mathrm{PS}}$ is the electricity generation from the biomass power plant, E_{cap} is the known energy capacity of the power station, U_{CES} is the average utilization factor of the power station (i.e. 70%), E_{CES} is the average efficiency of the power stations generating electricity from biomass (i.e. 40%) and E_{loss} is the efficiency loss of generating efficiency from postcombustion CO_2 capture technology (i.e. 8%, Zhao, Riensche, Blum, & Stolten, 2011; Markewitz, & Bongartz, 2015).

$$\mathrm{BE}_{\mathrm{CES}} = \frac{\mathrm{EI}_{\mathrm{PS}}}{1 - E_{\mathrm{loss}}} \times \mathrm{BE}_{\mathrm{cal}} \quad (2)$$

where $\mathrm{BE}_{\mathrm{CES}}$ is the annual demand of biomass from the power station and $\mathrm{BE}_{\mathrm{cal}}$ is the net calorific content of distinct bioenergy crops.

The biomass demands from the CHP in DES were calculated using Equation (3).

$$\mathrm{BE}_{\mathrm{DES}} = \left(H_{\mathrm{dem}} + \mathrm{ELC}_{\mathrm{dem}}\right) / \mathrm{BE}_{\mathrm{cal}} \times E_{\mathrm{DES}} \times \left(1 - E_{\mathrm{loss}}\right) \quad (3)$$

where $\mathrm{BE}_{\mathrm{DES}}$ is the annual demand of biomass from the CHP station, H_{dem} represents the domestic and nondomestic heat demand for the year 2050 across an indicative search radius of 5 km (78.5 km^2) surrounding the CHP stations, $\mathrm{ELC}_{\mathrm{dem}}$ is the electricity generation from CHP which has a fix proportion to heat provision of a CHP plant, E_{DES} is the average energy generation efficiency of the CHP station (i.e. $\mathrm{ELC}_{\mathrm{dem}}/H_{\mathrm{dem}}$ = 35%/45% = 0.778), E_{loss} is the efficiency loss of generating efficiency from postcombustion CO_2 capture technology (i.e. 8%) and $\mathrm{BE}_{\mathrm{cal}}$ is the net calorific content of distinct bioenergy crops.

2.4 | Environmental impact from bioenergy production on air, water and soil quality

The marginal arable land that underwent LUC to grow bioenergy crops was assumed to have previously received average annual fertilizer *N* rates similar to wheat cultivations of 221 kg N/ha. Permanent grassland was assumed to have received annual soil *N* inputs from synthetic fertilizers of 85 kg N/ha (N_{synt}), and 40 kg N/ha (N_{org}) from urine and dung *N* deposited by grazing animals. *Miscanthus*, SRC and SRF were assumed to be annually fertilized with 30, 60 and 45 kg N/ha respectively (Richards et al., 2017). In order to separate out the net effect of LUC on the soil itself, when calculating the GHG emissions associated with bioenergy production, we excluded the C stored in the harvested biomass, and all associated cultivation and harvesting emissions such as from machinery and fertilizer production/transport, since these are small in the total life-cycle emissions (Hastings, 2017; Richards et al., 2017).

The net environmental effects of producing bioenergy crops were reported as a sustainability indicator of the impact of LUC on air, water and soil quality. In particular, net changes in soil organic carbon (SOC) stocks are used as an indicator of the soil quality. The losses of anthropogenic fertilizer *N* inputs through atmospheric emissions of soil ammonia (NH_3-N) provided an indicator of air quality (A_{NH_3}). Losses of fertilizer *N* inputs through leaching and run-off of soil nitrate (NO_3^--N), causing eutrophication of aquatic systems, were used as an indicator of water quality (W_{NO_3}).

SOC change was obtained from the ELUM Software Package (Pogson et al., 2016), which summarizes SOC changes simulated using the ECOSSE model (Smith et al., 2010) over a 35 year period (nominally from 2015 to 2050) with the medium climate change scenario (UKCP-09; Richards et al., 2017). SOC stock changes within the top 1 m of the soil profile were balanced between soil organic matter decomposition rates and the annual organic *C* input from leaf and stubble after harvest (peak yield – harvest offtake).

Drawing on the IPCC (2006), A_{NH_3} was calculated using Equation (4):

$$A_{\mathrm{NH}_3} = N_{\mathrm{input}} \times R_{\mathrm{vol}} \quad (4)$$

where A_{NH_3} is the annual losses of NH_3-N, N_{input} is the annual amount of fertilizer *N* input entering the soil and R_{vol} is the annual fraction of soil *N* that volatilizes as ammonia. Whereas W_{NO_3} was calculated using Equations (5) and (6):

$$N_{\mathrm{SOM}} = \sum_{\mathrm{LU}} \left[\left(\Delta C_{\mathrm{LU}} \times \frac{1}{R_{\mathrm{C:N}}}\right) \times 1{,}000\right] \quad (5)$$

$$W_{\mathrm{NO}_3} = \left(N_{\mathrm{synt}} + N_{\mathrm{org}} + N_{\mathrm{SOM}}\right) \times R_{\mathrm{leac}} \quad (6)$$

where N_{SOM} is the annual amount of *N* mineralized associated with the loss of soil organic matter (SOM) from LUC, ΔC_{LU} is the average annual loss of soil *C* from LUC in arable and grassland and $R_{C:N}$ is the default C:N ratio of SOM. W_{NO_3} is the loss of NO_3^--N, N_{synt} and N_{org} the annual amount of synthetic and organic fertilizer *N* entering the soil, R_{leac} is the fraction of soil *N* mineralized and loss through leaching and run-off in water. Table 1 summarizes the value and unit of the parameters used in the calculations. For consistency and ease of comparison across the indicators SOC, A_{NH_3} and W_{NO_3}, we reported with positive and negative sign to represent net increased or reduced losses from the environment from LUC respectively.

TABLE 1 Values and units of the technical parameters used in the calculations of the environmental impact from bioenergy production, and greenhouse gas emissions from bioenergy with carbon capture and storage

Parameter	Unit	Value
BE_{cal} (*Miscanthus*)[a]	GJ/odt	14.55
BE $_{cal}$ (SRC and SRF)[a]	GJ/odt	7.5
BE-EF	kg_{CO_2eq}/GJ	
C_{coef}	%	10
C_{conc}	%	50
CCS	t_{CO_2}/year	
C_f	$kg_{CO_2\text{-}eq}$/t	49.36
C_m	mol	12
CO_{2m}	mol	44
BE_{CES}	Mt/year	
BE_{CES}	Mt/year	
E_{BE}	GJ	
E_{cap}	MWh	
E_{CES} biomass	%	40
E_{DES} CHP (elec. + heat)	%	80
E_{loss}	%	8
GHG_{com}	$t_{CO_2\text{-}eq}$/year	
F_{GHG}	$t_{CO_2\text{-}eq}$/year	
W_{NO_3}	$t_{NO_3\text{-}N}$/year	
A_{N_2O}	$t_{N_2O\text{-}N}$/year	
SOC	$t_{CO_2\text{-}C}$/year	
GHG_{trans}	$t_{CO_2\text{-}eq}$/year	
A_{NH_3}	$t_{NH_3\text{-}N}$/year	
N_{SOM}	t_N/year	
N_{Synt}	t_N/year	
N_{org}	t_N/year	
$R_{C:N}$		15
R_{leac}	$t_N/t_{N\ input}$	0.3
R_{vol}	$t_{NH_3\text{-}N\ volatilised}/t_{N\ input}$	0.1
U_{CES}	%	70
Y	t_{DM}/ha	

[a]The net calorific content of *Miscanthus*, short rotation coppice (SRC) and short rotation forestry (SRF) accounts for the energy penalties derived from the latent heat of water (i.e. 2.264 kJ/kg) at the normal harvest moisture content of *Miscanthus* (i.e. 14%) and SRC or SRF (i.e. 50%), and from the crop establishment and chipping energy costs (i.e. 1 GJ/odt).

2.5 | GHG emissions from BECCS

The GHG emissions associated with BECCS included the negative and positive emissions from bioenergy crop production, supply and combustion and postcombustion CO_2 capture in the power stations, and were reported as CO_2eq. The annual net balance associated with LUC for bioenergy crop production (F_{GHG}) corresponded to the sum of direct net GHG emissions from SOC change and N_2O obtained from the ELUM Software Package (Pogson et al., 2016), as originally simulated with the ECOSSE model (Smith et al., 2010), as described in Richards et al. (2017) and indirect emissions corresponding to A_{NH_3}, W_{NO_3}.

The land emissions associated with LUC to bioenergy crops were also reported as the ratio of F_{GHG} per unit of energy potentially generated from the biomass combustion in CES and DES, hereafter called the bioenergy crop emission factor (BE-EF). BE-EF represents the intensity of the LUC effect per unit of bioenergy produced, and was calculated using Equations (7) and (8).

$$\text{BE-EF} = \left(F_{GHG}/35\right)/E_{BE} \tag{7}$$

$$E_{BE.i} = Y_i \times BE_{cal.i} \times E_{CES/DES} \tag{8}$$

where BE-EF is the annual emission factor for a distinct bioenergy crop supply chain (i.e. *Miscanthus*, SRC willow, SRC poplar or SRF), F_{GHG} is the cumulative net GHG balance in LUC over 35 years (nominally from 2015 to 2050), E_{BE} is the energy generation from distinct bioenergy crops (i), Y_i is the annual harvested yield of distinct bioenergy crops, $BE_{cal.i}$ is the net calorific content of *Miscanthus*, SRC and SRF, which accounts for the latent heat of water (i.e. 2.264 kJ/kg) at the normal harvest moisture content of *Miscanthus* (i.e. 14%) and SRC or SRF (i.e. 50%), and from the crop establishment and chipping energy costs (i.e. 1 GJ/odt), $E_{CES/DES}$ is the generation efficiency of biomass power plants in CES (i.e. 40%) and CHP in DES (i.e. 80%), and 35 is the number of years used to estimate the annual F_{GHG}.

The negative emission from biomass combustion included the CO_2 produced during biomass combustion and captured in the power plants at a rate of 90%, assuming a broadly similar CO_2 capture efficiency across biomass power plants with varying efficiency. The CO_2 captured by the power station was calculated using Equation (9).

$$\text{CCS} = \left[Y \times C_{conc} \times \left(CO_{2m}/C_m\right)\right] \times 0.9 \tag{9}$$

where CCS is the annual CO_2 captured by postcombustion technology of distinct bioenergy crop types, assuming that 100% of the captured CO_2 is transferred in geological storage sites, C_{conc} is the carbon concentration in biomass, CO_{2m} is the molecular mass of CO_2 and C_m is the molecular mass of C. The combustion of biomass also produces positive GHG emissions of N_2O and CH_4 that were calculated using Equation (10).

$$GHG_{comb} = Y \times C_f \tag{10}$$

where GHG_{comb} is the annual N_2O and CH_4 emissions for distinct bioenergy crop supply chains, and C_f the conversion factor to estimate the N_2O and CH_4 emissions from wood chip combustion. Among the positive CCS emissions, we included the CO_2 not captured during the postcombustion process (CCS_{emiss}), which corresponded to 10% of the total CO_2 produced from biomass combustion (Equation 9). In addition, following the method reported in Hastings (2017), the positive GHG emissions from biomass transportation in bales (GHG_{trans}) to the power stations were assumed to be 21.6 $kg_{CO_2\text{-eq}}/t_{DM}$ for a round trip distance within catchment area of approximately 80 km.

3 | RESULTS

3.1 | Feedstock biomass production and demand from CES and DES

Across GB, 38 electrical power stations were found to emit above 37,000 t_{CO_2}/year, and thus included in the CES (Figure 1). Eight stations were located in the Yorkshire & Humber region, seven in the East Midlands, five in Wales and in the South East, four in the Eastern region, three in the North West, two in Scotland and in the South West and one station each in the West Midlands and North East region. Based on the capacity of the power stations and the commitment of combusting only feedstock biomass, the overall demand of biomass in the CES is 170.8 Mt for *Miscanthus* biomass or approximately 331 Mt of SRC and SRF biomass. Considering the sustainable LUC scenario (grades 4 and 5 land only), the combustion of the domestic biomass annually produced in CES corresponds to approximately 57.8 PJ/year of bioenergy, which is approximately 2.3% of

Region	CA	Site	Energy Demand	Biomass Supply					Energy Supply
				Yield	*Miscanthus*	SRC P	SRC W	SRF	
Yorkshire & Humber	1	Ferrybridge C	121.23	0.38	18.6%	23.1%	2.1%	56.2%	2.8%
East Midlands	2	Corby	23.90	0.13	12.3%	8.8%		78.9%	4.4%
Eastern	3	Coryton	47.68	0.07	12.9%	5.6%		81.5%	1.2%
East Midlands	4	Cottam	119.68	0.09	13.9%	8.6%		77.5%	0.7%
East Midlands	5	West Burton B	79.39	0.01	26.9%	9.5%		63.6%	0.1%
Wales	6	Uskmouth	13.59	0.38	50.1%	2.0%		47.9%	31.3%
South East	7	Marchwood	50.19	0.26	60.0%	0.1%	1.2%	38.6%	6.2%
East Midlands	8	Staythorpe	105.62	0.23	34.2%	3.5%		62.3%	2.2%
Wales	9	Pembroke	129.93	0.52	99.7%		0.3%	0.0%	5.8%
South East	10	Damhead Creek	47.98	0.02	50.9%			49.1%	0.5%
South West	11	Langage Energy Centre	53.94	0.26	85.8%	13.7%		0.4%	6.6%
North East	12	Lynemouth	25.03	0.30		71.6%	3.5%	24.9%	9.1%
North West	13	Fiddlers Ferry	116.88	0.18	16.5%	37.9%	1.0%	44.6%	1.4%
North West	14	Fellside CHP Plant	10.73	0.10	5.4%	88.8%	5.7%	0.0%	7.2%
Eastern	15	Great Yarmouth	25.03	0.09	5.3%			94.7%	2.7%
Yorkshire & Humber	16	South Humber	78.08	0.01	31.8%	30.9%		37.3%	0.2%
Eastern	17	Little Barford	42.91	0.06				100.0%	1.1%
South East	18	Didcot B	87.62	0.71	11.1%	1.4%		87.5%	6.7%
Wales	19	Aberthaw B	94.53	0.07	84.6%	3.2%	1.0%	11.2%	0.9%
Yorkshire & Humber	20	Drax	118.01	0.04	68.4%	6.0%		25.7%	0.4%
Yorkshire & Humber	21	Keadby	42.32						0.0%
Yorkshire & Humber	22	Killingholme 1	35.76	0.003		21.4%		78.6%	0.1%
South East	23	Medway	41.72	0.01	13.0%			87.0%	0.2%
Wales	24	Uskmouth B	21.64	0.002	30.6%			69.4%	0.1%
North West	25	Rocksavage	48.28	0.08	24.0%	1.5%	1.3%	73.1%	3.6%
West Midlands	26	Rugeley B	59.60	0.53	11.0%	23.4%		65.6%	9.1%
Yorkshire & Humber	27	Saltend	71.52						0.0%
Eastern	28	Rye House	42.62	0.003		18.9%		81.1%	0.0%
South West	29	Seabank	48.40	0.08	59.2%			40.8%	2.1%
South East	30	Shoreham	25.03	0.30	63.1%			36.9%	7.5%
East Midlands	31	Sutton Bridge	48.81	0.05	20.2%	1.9%		77.9%	1.6%
East Midlands	32	West Burton	119.92						0.0%
Scotland	33	Longannet	143.05	0.27	8.4%	56.4%	2.0%	33.3%	4.4%
Scotland	34	Peterhead	70.33	0.08	4.8%	78.4%	0.6%	16.3%	0.5%
Yorkshire & Humber	35	Eggborough	116.82						0.0%
Wales	36	Baglan Bay	30.99	0.34	80.4%	19.4%	0.2%	0.0%	6.4%
Yorkshire & Humber	37	Immingham	73.91						0.0%
East Midlands	38	Spalding	52.45						0.0%

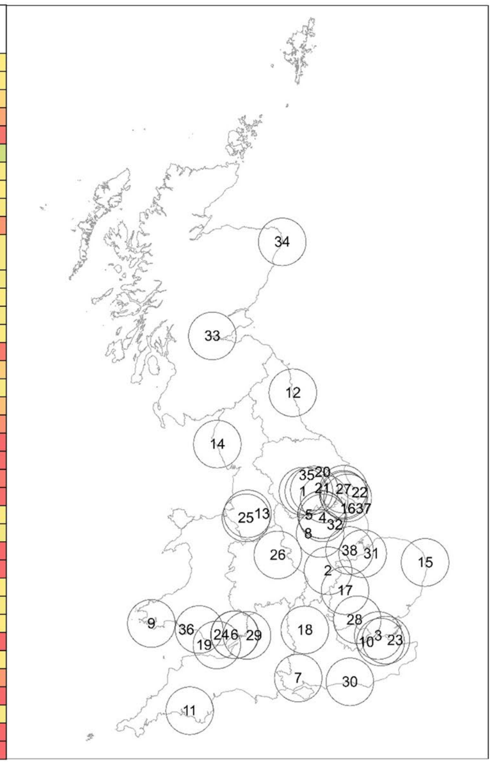

FIGURE 1 Domestic biomass supply of *Miscanthus*, short rotation coppice poplar (SRC P), short rotation coppice willow (SRC W), and short rotation forestry (SRF) from land-use change in low quality grade agricultural land (i.e. ALC 4 and 5) across the centralized energy system (CES). The map on the right reports the location across Great Britain of the biomass catchment areas corresponding to electrical biomass power stations, and located at the same locations of existing large electrical power plants reported to emit in 2015 more than 10,000 $t_{CO_2\text{-}C}$/year . The table on the left reports the catchment area of each power station, the energy demands from the stations (PJ/year), the domestic biomass supply of bioenergy crops (Yield, Mt_{DM}/year), the percentage of contribution from different bioenergy crop supply chain, and the potential energy supply from the combustion of domestic biomass across CES (%)

TABLE 2 Summary across the centralized (CES) of the agricultural land available, the annual cumulative biomass production of *Miscanthus*, short rotation coppice (SRC) poplar, SRC willow, and short rotation forestry (SRF) in arable and grassland with productivity potential ≥9 t_{DM}/ha , the net soil quality change in land-use change (LUC) to grow bioenergy crop which corresponds to the net change in soil organic carbon, the air quality indicator which corresponds to the net *N* losses in LUC from ammonia (NH_3) volatilization, and the water quality indicator which corresponds to the net *N* losses in LUC leaching and runoff of soil nitrate (NO_3^-)

	Agricultural land available (kha)								Biomass production (kt_{DM}/year)		Net LUC effects to bioenergy crop production: Soil quality ($t_{CO_2\text{-}C}$/year)		Air quality ($t_{NH_3\text{-}N}$/year)		Water quality ($t_{NO_3\text{-}N}$/year)	
CES	Arable	ALC 3	ALC 4	ALC 5	Grass	ALC 3	ALC 4	ALC 5	Arable	Grass	Arable	Grass	Arable	Grass	Arable	Grass
BE type																
Miscanthus	329	88%	11%	1%	294	67%	30%	3%	4,886	4,527	−118,461	42,686	−6,285	−3,963	−18,497	−7,484
SRF	1,055	92%	8%	0%	587	83%	16%	1%	14,321	8,082	−653,775	10,546	−18,571	−7,049	−60,401	−11,244
SRC willow	3	94%	5%	1%	4	43%	41%	16%	41	65	−304	1,272	−55	−46	−189	−59
SRC poplar	206	92%	7%	1%	213	76%	21%	3%	2,733	3,052	−21,523	55,778	−3,324	−2,240	−11,245	−3,038
Total	1,594				1,099				21,981	15,726	−794,063	110,283	−28,235	−13,299	−90,332	−21,826
Regions																
East Midlands	436	95%	5%	0.0%	163	82%	18%	0.0%	5,615	2,132	−245,285	2,473	−7,691	−1,959	−24,965	−3,220
Eastern	245	98%	2%	0.0%	84	95%	5%	0.0%	3,249	1,121	−166,180	−1,461	−4,342	−1,016	−14,082	−1,727
London	2	91%	9%	0.0%	2	94%	6%	0.0%	31	26	−1,223	99	−43	−25	−139	−41
North East	55	88%	12%	0.2%	66	61%	30%	9.0%	717	871	−8,551	14,068	−907	−713	−3,055	−1,010
North West	65	91%	6%	2.4%	94	79%	14%	7.3%	953	1,404	−14,549	15,506	−1,116	−1,079	−3,578	−1,617
Scotland	93	93%	5%	1.9%	98	76%	18%	5.2%	1,352	1,437	−20,780	22,615	−1,542	−1,081	−5,030	−1,499
South East	268	66%	34%	0.0%	189	61%	39%	0.1%	3,877	2,663	−127,206	8,938	−4,888	−2,380	−15,216	−4,183
South West	145	92%	8%	0.2%	119	82%	17%	0.5%	2,219	1,841	−63,821	9,893	−2,669	−1,526	−8,131	−2,755
Wales	39	53%	44%	3.6%	136	38%	51%	11.4%	591	2,175	−8,773	27,332	−714	−1,776	−2,134	−3,002
West Midlands	69	84%	16%	0.1%	80	65%	34%	0.7%	958	1,125	−32,632	6,332	−1,214	−943	−3,945	−1,466
Yorkshire & Humber	176	89%	11%	0.2%	67	55%	40%	5.7%	2,418	930	−105,063	4,487	−3,109	−801	−10,059	−1,306
Total	1,594				1,099				21,981	15,726	−794,063	110,283	−28,235	−13,299	−90,332	−21,826

The extent of agricultural land can be further partition among different quality grades (from agricultural land classification, ALC 3 to 5) by multiplying the value in kha by the corresponding proportion of land in each ALC. The Positive and negative value correspond to potential increase and reduction of emissions to the environment, respectively.

the overall energy output of the 38 power stations (2485.2 PJ; Figure 1). While in the maximizing scenario (grades 3, 4 and 5 land), the energy contribution of domestic biomass increases to 5.6% (i.e. 140 PJ/year) of the overall energy output of the power stations in CES. However, due to the clustering of power stations, several catchment areas overlapped in the regions Yorkshire & Humber, Wales and South East, leading to an overall reduction in the potential supply of biomass in CES. Table 2 summarizes the potential land extent, biomass production and environmental effects from bioenergy crop production across CES. In the sustainable LUC scenario, CES provides approximately 0.14 and 0.25 Mha of land, and 2 and 3.7 Mt_{DM}/year of feedstock biomass on arable and grassland respectively. Whereas, in the maximizing scenario, the catchment areas of CES provide up to 1.59, and 1.1 Mha of arable and grassland for bioenergy crops, and up to 22 and 15.7 Mt_{DM}/year of domestic biomass respectively. Biomass feedstock production varies based on the quality grade of arable and grassland, and approximately 85%, 14% and 1% of the bioenergy crop production occurs on land classes 3, 4 and 5 respectively. In arable land, the potential contribution from different bioenergy crop genotypes is 21%, 66%, 0.2% and 13% from *Miscanthus*, SRF, SRC willow and SRC poplar respectively. In grasslands, the overall contribution was 27%, 53%, 0.4% and 19% for *Miscanthus*, SRF, SRC willow and SRC poplar respectively.

DES includes 59 CHP stations with an annual energy output ranging from 2 to 65.2 PJ/year (Figure 2). Eleven CHP stations are located in the North West region, twelve in the South West, nine in the Yorkshire & Humber and South East regions, eight in Scotland, six in the West Midlands, four in the London and East Midlands regions, three in Wales and two in the North East region. Based on the thermal energy efficiency of the CHP stations (80%), and the energy penalty associated with the postcombustion CO_2 capture technology (8%), the cumulative biomass demand in DES is 43.9 Mt for *Miscanthus*, or 85.1 Mt for SRC and SRF. In the sustainable LUC scenario, the combustion of domestic biomass in CHPs provides approximately 68 PJ/year (i.e. 11% of the total energy output from the 59 CHPs) from 2.6 and 4.7 Mt_{DM}/year of biomass produced across 0.2 and 0.3 Mha of land on arable and grassland respectively. In particular, on former arable land, the potential biomass production of *Miscanthus*, SRF, SRC willow and SRC poplar is approximately 17%, 68%, 0.1% and 15% respectively. On grassland, the biomass contribution is 21%, 55%, 0.2% and 24% from *Miscanthus*, SRF, SRC willow and SRC poplar respectively. In the maximizing scenario, the bioenergy produced from the domestic annual biomass across DES (i.e. 315 PJ/year) could provide up to 49% of the energy output from the CHPs (Figure 2). Excluding the overlapping section of the catchment areas of the CHP stations, the total area in DES is 1.8 Mha in arable land, and 1.4 Mha in grassland. This provides approximately 24.1 and 20.3 Mt_{DM}/year of feedstock biomass across arable and grassland respectively (Table 3).

3.2 | Impact of bioenergy production on air, water and soil quality

In all LUC transitions, bioenergy crops contribute to improving air and water quality by reducing agricultural ammonia and nitrate pollution. Overall, across the maximizing scenario of CES and DES, the potential reduction in air pollution from ammonia emissions is −41.5 and −47.8 $kt_{NH_3\text{-}N}$/year respectively. The potential net reduction in water pollution ranges from −112 to −120 $kt_{NO_3\text{-}N}$/year in CES and DES respectively (Tables 2 and 3). On a per-hectare basis, the environmental impact is very similar between the sustainable and maximizing LUC scenarios. The net environmental reduction in air pollution from bioenergy crop production is approximately −17 $kg_{NH_3\text{-}N}$ $ha^{-1}year^{-1}$ on arable land and −12 $kg_{NH_3\text{-}N}$ ha^{-1} $year^{-1}$ on grassland. The potential annual net environmental reduction in water pollution is approximately −53 and −20 $kg_{NO_3\text{-}N}$ ha^{-1} $year^{-1}$ on arable and grassland respectively. While air and water quality potentially improve across all LUC transitions in arable and grassland, the production of bioenergy crop on former grassland causes reduction in soil quality through SOC losses. On a per-hectare basis, the potential net losses of SOC on grassland vary between 150 and 100 $kg_{SOC\text{-}C}$ ha^{-1} $year^{-1}$ in the sustainable and maximizing LUC scenarios respectively. On arable land, the LUC to bioenergy crops offer net increases in SOC ranging from −370 to −470 $kg_{SOC\text{-}C}$ ha^{-1} $year^{-1}$ in the sustainable and maximizing LUC scenarios respectively.

3.3 | Net GHG balance from bioenergy crop production

The net effect of LUC on GHG emissions varied depending on the type of land-use being converted, the potential productivity of each bioenergy crop across distinct land quality grades, the geographical location and the extent of biomass catchment areas needed to satisfy the energy demands in CES and DES. Combining the direct and indirect annual net GHG emissions from LUC, the annual net GHG balance in the bioenergy supply chains (F_{GHG}) is negative in both marginal arable land and grasslands (i.e. reduced emissions). When negative in sign, F_{GHG} represents a potential GGR strategy to reduce the emission from the agricultural sector in GB. Overall *Miscanthus* is the bioenergy crop with the highest potential reduction in direct and indirect soil GHG emissions. On former arable land, the reduction in GHG emissions from LUC is approximately −37, −35 and −30 t_{CO_2eq} ha^{-1} $year^{-1}$ for *Miscanthus*, SRF and SRC respectively. Meanwhile, on

TABLE 3 Summary across the distributed energy system (DES) of the agricultural land available, the annual cumulative biomass production of *Miscanthus*, short rotation coppice (SRC) poplar, SRC willow, and short rotation forestry (SRF) in arable and grassland with productivity potential ≥9 t_{DM}/ha, the net soil quality change in land-use change (LUC) to grow bioenergy crops which corresponds to the net change in soil organic carbon, the air quality indicator which corresponds to the net *N* losses in LUC from ammonia (NH_3) volatilization, and the water quality indicator which corresponds to the net *N* losses in LUC leaching and runoff of soil nitrate (NO_3^-)

	Land available (kha)								BE production (kt_{DM}/year)		Net LUC effects to bioenergy crop production: Soil quality ($t_{CO_2\text{-}C}$/year)		Air quality ($t_{NH_3\text{-}N}$/year)		Water quality ($t_{NO_3\text{-}N}$/year)	
DES	**Arable**	**ALC 3**	**ALC 4**	**ALC 5**	**Grass**	**ALC 3**	**ALC 4**	**ALC 5**	**Arable**	**Grass**	**Arable**	**Grass**	**Arable**	**Grass**	**Arable**	**Grass**
BE type																
Miscanthus	274	83%	16%	1%	283	72%	25%	3%	4,093	4,269	−102,840	32,792	−5,231	−3,827	−15,692	−7,423
SRF	1,196	91%	9%	0.1%	808	82%	18%	0.4%	16,301	11,173	−694,605	16,134	−21,052	−9,699	−63,156	−15,438
SRC willow	2	95%	4%	1%	3	38%	38%	25%	24	37	−152	676	−32	−26	−97	−35
SRC poplar	282	91%	8%	1%	324	71%	27%	2%	3,706	4,792	−26,026	91,327	−4,542	−3,402	−13,625	−4,492
Total	1,754				1,418				24,125	20,271	−823,623	140,930	−30,857	−16,954	−92,570	−27,388
Regions																
East Midlands	440	93%	7%	0%	187	67%	27%	6%	5,715	2,483	−244,997	4,056	−7,756	−2,260	−23,267	−3,741
Eastern	57	99%	1%	0%	30	96%	4%	0%	769	404	−35,825	-588	−999	−358	−2,996	−603
London	2	91%	9%	0%	2	94%	6%	0%	32	26	−1,225	102	−43	−25	−130	−41
North East	97	70%	27%	3%	102	44%	47%	9%	1,249	1,341	−24,075	18,838	−1,611	−1,122	−4,834	−1,610
North West	64	89%	7%	3%	123	71%	22%	7%	940	1,977	−14,083	24,771	−1,091	−1,382	−3,273	−1,988
Scotland	178	92%	6%	2%	171	68%	26%	6%	2,457	2,421	−47,989	38,949	−3,010	−1,909	−9,030	−2,623
South East	333	85%	15%	0%	246	81%	19%	0%	4,772	3,434	−154,952	11,469	−6,057	−3,088	−18,172	−5,398
South West	118	83%	17%	1%	189	81%	19%	0%	1,717	2,885	−53,956	14,952	−2,119	−2,421	−6,356	−4,347
Wales	30	76%	22%	2%	62	66%	28%	6%	445	932	−7,539	8,592	−547	−776	−1,641	−1,264
West Midlands	197	82%	18%	0%	186	66%	33%	1%	2,793	2,654	−116,604	5,731	−3,467	−2,211	−10,402	−3,578
Yorkshire & Humber	238	93%	7%	0%	121	50%	47%	2%	3,235	1,713	−122,378	14,059	−4,156	−1,403	−12,468	−2,195
Total	1,754				1,418				24,125	20,271	−823,623	140,930	−30,857	−16,954	−92,570	−27,388

The extent of agricultural land can be further partition among different quality grades (from agricultural land classification, ALC 3 to 5) by multiplying the value in kha by the corresponding proportion of land in each ALC. The Positive and negative value correspond to potential increase and reduction of emissions to the environment, respectively.

Region	CA	Energy Demand	Biomass Supply					Energy Supply
			Yield	*Miscanthus*	SRC P	SRC W	SRF	
South West	1	6.48	0.29	88.0%	11.7%		0.3%	62.0%
South East	2	9.54	0.30	61.0%			39.0%	37.1%
South East	3	8.37	0.26	65.6%	0.1%	0.1%	34.2%	37.3%
South West	4	1.99	0.48	46.9%			53.1%	100.0%
South West	5	13.47	0.18	50.4%	0.9%		48.7%	15.0%
London	6	14.18	0.16	51.0%			49.0%	12.8%
South East	7	9.14	0.32	18.7%	0.1%		81.2%	30.8%
South East	8	3.64	0.07	20.7%	3.8%		75.6%	18.2%
Yorkshire & Humber	9	9.48	0.05	31.8%	22.5%		45.7%	5.1%
South East	10	8.24	0.001	4.3%			95.7%	0.1%
South East	11	7.91						
London	12	65.23	0.003		20.8%		79.2%	0.03%
Wales	13	14.00	0.17	82.4%	4.7%		12.8%	15.8%
South East	14	8.70	0.610	5.7%	2.5%		91.8%	55.7%
London	15	13.87	0.001				100.0%	0.0%
Wales	16	7.89	0.08	3.3%			96.7%	7.8%
South East	17	7.57	0.02	32.6%			67.4%	2.1%
East Midlands	18	16.25	0.21	7.7%	3.2%		89.1%	10.7%
London	19	14.41	0.01	1.0%			99.0%	0.3%
Wales	20	4.00	0.06	50.4%	0.8%		48.9%	16.3%
South East	21	4.48	0.14	4.3%	1.2%		94.4%	24.2%
West Midlands	22	12.35	0.09	5.5%	1.1%		93.4%	5.9%
West Midlands	23	19.78	0.10	3.1%	2.7%		94.1%	3.9%
West Midlands	24	13.77	0.06	2.5%	6.8%		90.8%	3.6%
West Midlands	25	12.14	0.12	1.0%	14.9%		84.2%	7.7%
West Midlands	26	5.13	0.42	28.7%	20.2%		51.2%	78.9%
East Midlands	27	4.41	0.08	23.4%	3.3%		73.3%	17.1%
East Midlands	28	13.50	0.08	71.5%	1.9%	0.9%	25.7%	7.1%
East Midlands	29	15.42	0.01	2.0%			98.0%	0.5%
West Midlands	30	9.62	0.24	7.7%	59.4%	0.6%	32.3%	19.8%
North West	31	4.30	0.02	44.7%	46.0%		9.3%	5.4%
North West	32	3.15	0.06	7.7%	11.4%		80.8%	14.3%
Yorkshire & Humber	33	14.66	0.20	31.8%	28.2%		40.0%	13.4%
Yorkshire & Humber	34	6.49	0.04	25.8%	28.3%		46.0%	6.4%
North West	35	8.51	0.14	28.4%	16.2%	0.5%	54.9%	15.7%
North West	36	9.82	0.02	8.5%	91.5%			1.6%
North West	37	15.91	0.00	25.8%	72.5%		1.8%	0.2%
North West	38	24.12	0.04	2.9%	97.1%			1.3%
North West	39	9.34	0.00		100.0%			0.1%
North West	40	8.00	0.02		100.0%			1.5%
Yorkshire & Humber	41	7.93	0.07		4.5%		95.5%	6.5%
North West	42	3.78	0.23	0.5%	99.0%	0.5%		45.5%
Yorkshire & Humber	43	8.50	0.10	10.3%	62.9%	1.0%	25.9%	10.0%
Yorkshire & Humber	44	4.88	0.04	5.0%	14.9%		80.1%	5.8%
Scotland	45	10.26	0.17	1.6%	72.8%	0.1%	25.6%	12.3%
North West	46	5.80	0.04	6.3%	86.7%	7.1%		5.6%
Yorkshire & Humber	47	13.85	0.06	25.5%	49.6%	0.3%	24.5%	4.3%
Yorkshire & Humber	48	16.08	0.00	0.1%			99.9%	0.1%
Yorkshire & Humber	49	12.17	0.04	78.3%	3.8%		18.0%	4.3%
North East	50	17.27	0.39		64.6%	1.6%	33.8%	17.1%
North East	51	5.33	0.21	5.6%	42.5%	1.0%	50.9%	32.0%
North West	52	4.50	0.05	0.0%	98.5%	1.5%		7.6%
Scotland	53	7.45	0.28	8.1%	79.5%	1.3%	11.1%	30.5%
Scotland	54	6.56	0.16	6.1%	30.3%		63.6%	19.6%
Scotland	55	19.42	0.12	2.0%	64.7%		33.2%	4.8%
Scotland	56	7.62	0.07	8.1%	86.1%	0.8%	5.1%	7.8%
Scotland	57	20.67	0.01		100.0%			0.5%
Scotland	58	3.48	0.01	0.2%	81.4%		18.4%	1.8%
Scotland	59	3.38	0.06	5.1%	75.2%	5.3%	14.3%	14.9%

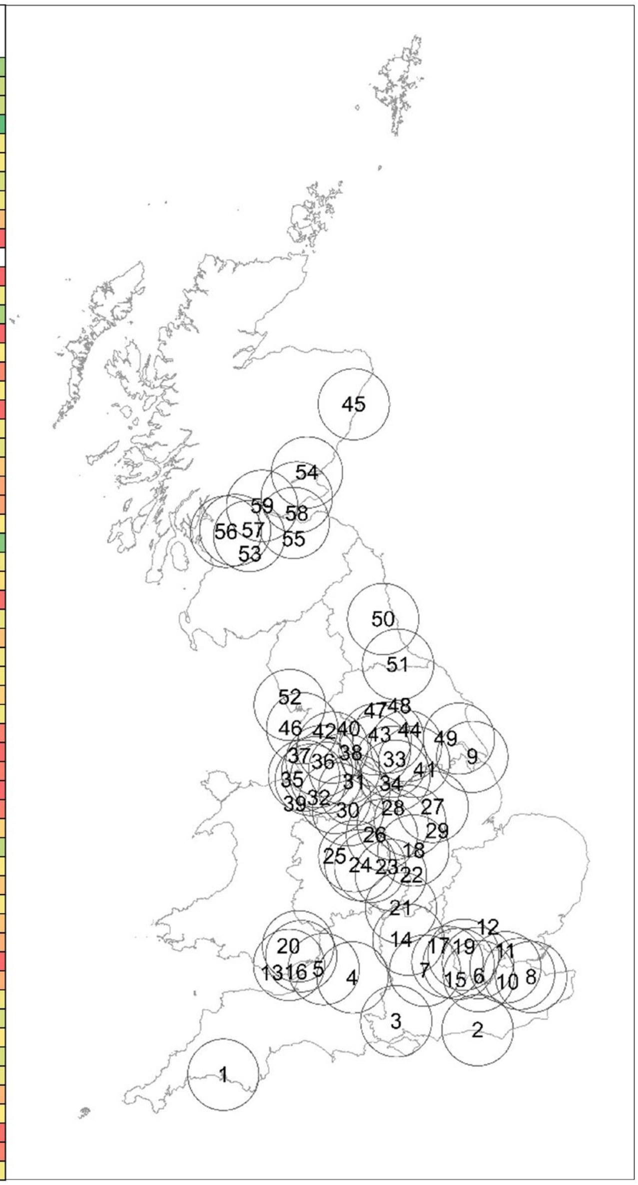

FIGURE 2 Annual biomass demands and supply rates of *Miscanthus*, short rotation coppice poplar (SRC P), short rotation coppice willow (SRC W), and short rotation forestry (SRF) from land-use change in low quality grade agricultural land (i.e. ALC 4 and 5) across the distributed energy system (DES). The map on the right reports the location across Great Britain of the biomass fuelled Combined Heat and Power (CHP) stations, and highlights their biomass catchment areas (CA). CHP energy inputs included both annual domestic and non-domestic heat demands for the year 2050 within district heating search areas of 5 km radius. The table on the left reports the catchment area of each CHP station, the energy demands from the stations (PJ/year), the domestic biomass supply of bioenergy crops (Yield, Mt_{DM}/year), the percentage of contribution from different bioenergy crop supply chain, and the potential energy supply from the combustion of domestic biomass across DES (%)

former grasslands, the net emissions from SOC changes and the direct soil N_2O emissions reduced the mitigation of GHG emission from bioenergy crop to approximately −18, −14 and −10 t_{CO_2eq} ha^{-1} $year^{-1}$ for *Miscanthus*, SRF and SRC respectively. Overall in the sustainable LUC scenario, F_{GHG} is approximately −9 and −11 Mt_{CO_2eq}/year in CES and DES respectively. In the maximizing scenario of CES, F_{GHG} is approximately −75 Mt_{CO_2eq}/year (i.e. −59 and −16 Mt_{CO_2eq}/year in arable and grassland). Across DES, F_{GHG} is approximately −82 Mt_{CO_2eq}/year (i.e. −62 and −20 Mt_{CO_2eq}/year in arable and grassland; Table 4).

The GHG emission intensity from bioenergy crop production (BE-EF) varied depending on the potential productivity of biomass, the net calorific content of distinct bioenergy crops and the energy efficiency assumed for the power stations (i.e. 40% and 80% in CES and DES respectively). On average, in CES, BE-EF is −427 and −129 $kg_{CO_2eq}/GJ_{bioenergy}$ on former arable and grassland respectively (Figure S3). In

TABLE 4 Summary across the centralized (CES) and distributed (DES) energy systems of the cumulative greenhouse gas (GHG) mitigations (greenhouse gas removal, GGR) from land-use change (LUC) in arable and grasslands to grow *Miscanthus*, short rotation coppice (SRC) poplar, SRC willow, and short rotation forestry (SRF) (GGR - BE), CO_2 produced from combustion of biomass in power stations and captured by postcombustion capture process (CCS), total negative emissions from BECCS given by the sum of GGR-BE and CCS (NE-BECCS), and total positive emissions (PE-BECCS) given by the sum of GHG emissions from biomass transportation (GHG_{trans}), non-CO_2 emissions (i.e. CH_4 and N_2O) from biomass combustion in power stations (GHG_{comb}), and positive emissions from CCS_{emiss} (i.e. 10% CCS)

	CES				DES			
	Arable		Grassland		Arable		Grassland	
	Mt_{CO_2eq}	ALC 3 – 4 – 5 (%)	Mt_{CO_2eq}	ALC 3 – 4 – 5 (%)	Mt_{CO_2eq}	ALC 3 – 4 – 5 (%)	Mt_{CO_2eq}	ALC 3 – 4 – 5 (%)
GGR - BE								
Miscanthus	−12.15	88 – 11 – 1	−5.16	68 – 29 – 3	−10.26	84 – 16 – 1	−5.11	73 – 24 – 3
SRF	−39.82	92 – 8 – 0	−8.47	83 – 16 – 1	−42.46	91 – 9 – 0	−11.62	82 – 17 – 0
SRC Willow	−0.12	94 – 5 – 1	−0.04	48 – 38 – 15	−0.06	95 – 4 – 2	−0.03	42 – 36 – 22
SRC Poplar	−6.96	92 – 7 – 1	−2.24	78 – 20 – 2	−8.69	91 – 8 – 1	−3.31	73 – 25 – 1
Total	−59.05	92 – 8 – 0	−15.91	77 – 21 – 2	−61.47	90 – 10 – 0	−20.07	78 – 20 – 1
CCS								
Miscanthus	−8.06	88 – 11 – 1	−7.47	66 – 31 – 4	−6.75	88 – 11 – 1	−7.04	72 – 24 – 4
SRF	−23.63	92 – 8 – 0	−13.34	83 – 16 – 1	−26.90	91 – 9 – 0	−18.44	82 – 18 – 0
SRC Willow	−0.07	92 – 7 – 1	−0.11	40 – 43 – 17	−0.04	93 – 5 – 2	−0.06	33 – 41 – 26
SRC Poplar	−4.51	92 – 8 – 1	−5.04	76 – 22 – 3	−6.11	91 – 9 – 1	−7.91	69 – 29 – 2
Total	−36.27	91 – 9 – 0	−25.95	76 – 22 – 2	−39.81	90 – 10 – 0	−33.45	77 – 22 – 1

	Mt_{CO_2eq}	Mt_{CO_2eq}	Mt_{CO_2eq}	Mt_{CO_2eq}
NE-BECCS				
Miscanthus	−20.21	−12.63	−17.02	−12.16
SRF	−63.45	−21.80	−69.36	−30.06
SRC Willow	−0.18	−0.15	−0.10	−0.09
SRC Poplar	−11.47	−7.27	−14.80	−11.22
Total	−95.32	−41.86	−101.28	−53.52
PE-BECCS				
GHG_{comb}	1.08	0.78	1.19	1.00
CCS_{emiss}	4.03	2.88	4.42	3.72
GHG_{transp}	0.48	0.34	0.52	0.44
Total	5.59	4.00	6.14	5.16

The potential CO_2 mitigation values of GGR-BE and CCS can be further partition among different agricultural land quality grades (from agricultural land classification, ALC 3 to 5) converted to grow bioenergy crops by multiplying the value $Mt_{CO2\text{-}eq}$/year by the corresponding ALC proportion.

DES, the average BE-EF is −199 and −67 $kg_{CO_2\text{-}eq}/GJ_{bioenergy}$ on former arable and grassland respectively (Figure S4). Across distinct bioenergy crop genotypes, GHG-EF is ranked: *Miscanthus* > SRC poplar > SRC willow > SRF.

3.4 | Mitigation potential from BECCS

Table 4 summarizes the annual cumulative negative CO_2 emissions (NE) from LUC to bioenergy crop and from postcombustion CO_2 capture (BECCS), and positive CO_2 emissions (PE) from GHG_{comb}, GHG_{trans} and CCS_{emiss}. By assuming postcombustion capture technology with 90% efficiency in both CES and DES, the overall combustion of domestic feedstock biomass produced in the sustainable LUC scenario leads to projected capture of approximately 18 Mt_{CO_2}/year across the power stations of CES and 23 Mt_{CO_2}/year in the CHP stations of DES. However, by increasing the potential LUC to grades 3, 4 and 5, the potential mitigation from BECCS increases to approximately 137 and 155 Mt_{CO_2}/year in CES and DES respectively. This suggests that in order to meet the target of 50 Mt_{CO_2}/year captured from BECCS by 2050, by using only domestic biomass, approximately 18 and 15 Mt_{CO_2}/year of the CO_2 mitigation

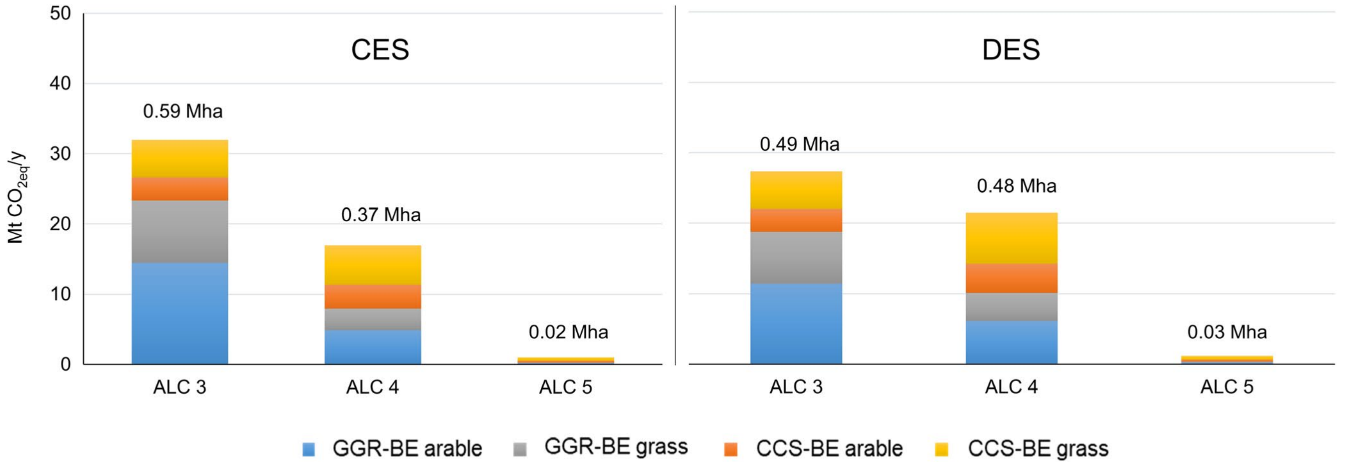

FIGURE 3 Summary of the CO_2 mitigation potential needed to meet the mitigation target of 50 Mt_{CO_2eq}/year by 2050 from bioenergy with carbon capture and storage in Great Britain. In the graph, the CO_2 mitigation potentials from the centralized (CES) and distributed (DES) energy systems are partitioned between greenhouse gas removal (GGR) from bioenergy crops production (GGR-BE), and CO_2 produced from combustion of bioenergy crops in power stations and captured by carbon and capture technology (CCS) across different arable and grassland quality grades (i.e. ALC 3, 4 and 5). Assuming short rotation forestry (SRF) as the reference feedstock biomass supplied to the power stations, to meet the mitigation target of 50 Mt_{CO_2eq}/year, in CES approximately 0.59 Mha of agricultural land of quality grade 3, and 0.39 Mha of grade 4 and 5 need to be converted to bioenergy production. While, in DES approximately 0.49 Mha of agricultural land of quality grade 3, and 0.51 Mha of grade 4 and 5 are needed for bioenergy production

potential of BECCS from agricultural land of grade 3 would need to be added to the CO_2 mitigated through the sustainable LUC scenario in CES and DES respectively (Figure 3). This, however, carries a much higher risk of displacing food production. By considering SRF as the reference feedstock biomass combusted in power stations for CES, the target of 50 Mt_{CO_2}/year would be met by converting 0.59 and 0.38 Mha of agricultural land of grade 3 and grades 4 and 5 respectively (Figure 3). While, in DES, 0.49 and 0.5 Mha of agricultural land of grade 3 and grades 4 and 5, respectively, would be needed (Figure 3).

The location of the power stations in regions with relatively low bioenergy potentials (e.g. London in DES), as well as the clustering and overlap of their catchment areas, limited the uniform supply of domestic biomass across the power stations. In some instances, the coastal location of large power stations, such as 34 and 37 in CES (Figure 1) reduced the extent of their catchment areas, limiting the access to locally sourced bioenergy. Consequently, in the sustainable LUC scenario, the combustion of domestic produced biomass from *Miscanthus* provides BECCS mitigation potentials of approximately 6.6 and 6 Mt_{CO_2}/year in CES and DES respectively. Using the biomass from SRC willow, the BECCS potential is 0.1 and 0.06 Mt_{CO_2}/year in CES and DES respectively. Use of domestic SRC poplar BECCS could deliver 2.7 and 4.8 Mt_{CO_2}/year of mitigation in CES and DES respectively. Use of domestically produced SRF could deliver approximately 8.6 and 11.8 Mt_{CO_2}/year of mitigation in CES and DES respectively (Table 4). Figure 4 shows the regional annual BECCS potential from CES and DES, derived from the net GHG mitigation from LUC to bioenergy crops and from CCS. As a consequence of the spatial distribution of arable land and grassland across GB, and the differing spatial productivity of the four bioenergy crop supply chains, BECCS potentials were higher for former grasslands across the western regions (dominated by grasslands), and higher in croplands across the eastern regions (dominated by arable lands) of GB. The South East, in particular, was the region with the highest mitigation potential from BECCS, ranging from 1.8 Mt_{CO_2}/year on former grassland in CES to 3.3 Mt_{CO_2}/year on former arable land in DES. London was the region with the lowest BECCS potential due to limited land availability for bioenergy crops.

The GHG emissions from BECCS range from 1.2 to 1.85 Mt_{CO_2}/year in the sustainable LUC scenario of CES and DES respectively. However, by including agricultural land of grade 3, the GHG emission raises to 3.6 and 11.3 Mt_{CO_2}/year for CES and DES respectively (Table 4). In general, the intensity of the GHG emission of BECCS per unit of energy produced in the power station is higher in the maximizing scenario than in the sustainable LUC scenario, and higher in CES than DES. In particular, in CES, the GHG emission intensity from BECCS is approximately 68 and 21 g_{CO_2eq}/MJ in the maximizing and sustainable LUC scenario respectively. In DES, the GHG emission intensity is 36 and 27 g_{CO_2eq}/MJ in the maximizing and sustainable LUC scenario respectively.

4 | DISCUSSION

In the coming years, new governmental policies will be published by the UK government to meet the environmental

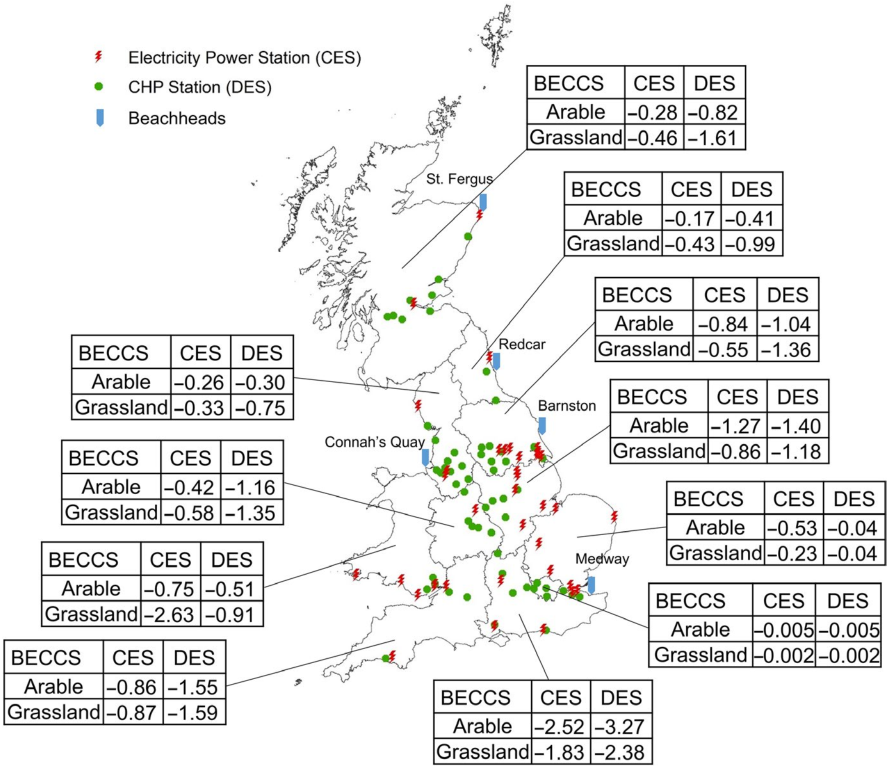

FIGURE 4 Regional summary of bioenergy with carbon capture and storage potential (Mt_{CO_2}/year) from bioenergy production on low quality arable and grasslands across Great Britain. In the map the symbols correspond to the location of the biomass power stations in the centralized (CES) and distributed (DES) energy systems, and the beachheads identified in the ETI carbon capture and storage (CCS) scenarios (ETI, 2016) to connect the onshore CO_2 transport infrastructures to offshore CO_2 storage sites

targets set out by the Climate Change Act 2008 (Committee on Climate Change, 2017, 2018). More effective policies are needed to reduce the emission intensity associated with agricultural activities, and to deliver the agreed emission reduction target of 4.5 Mt_{CO_2eq} from the agricultural sector as a whole. In addition, new strategies are required to permit the energy sector to achieve near-zero emissions, reducing the power generation emission intensity below the threshold of 100 g_{CO_2}/kWh by 2050. To meet this level of decarbonization, it is necessary to implement integrated cross-sectoral GGR mitigation strategies such as BECCS that permit positive synergies between the agricultural and energy sectors to be established (Smith et al., 2016). Previous research suggests that BECCS in the UK can mitigate between 20 and 70 Mt_{CO_2}/year with the potential of storing up to 1 Gt_{CO_2} offshore (ETI, 2016). To achieve this level of negative emissions, however, BECCS has to be deployed to a level sufficient to realize economies of scale both in the agricultural and energy sector. By 2050, the generation capacity in the United Kingdom is expected to increase by 268 GW, and up to 65% of the power generated will be local (FES, 2018). In the future energy scenarios developed by the National Grid, in particular, the climate mitigation targets set out for the energy sector will depend on the speed of decarbonization and level of decentralization of the power generation across the United Kingdom (FES, 2018). This suggests that two main pathways will allow the penetration of BECCS in the UK energy system: (a) integrating with existing large-scale centralized power stations, and (b) through the development of decentralized power generation systems. By focusing on the importance of decentralization and decarbonization for future energy scenarios, here we report a spatially explicit analysis of the climate mitigation potential of BECCS across centralized existing large-scale power stations, and industrial CHP stations distributed to meet the heat and power demands in 2050. The spatially explicit analysis reported here allows evaluation of the trade-off between centralized and DESs on land availability for bioenergy crop production, environmental sustainability of LUC to bioenergy production, biomass feedstock generation capacity and on the potential carbon implications of deploying BECCS across GB. Since the conversion of agricultural land to bioenergy production often constitutes the main LUC transition in climate mitigation scenarios, we focused our environmental analysis on the potential conversion of arable and grassland of medium and low quality grade (i.e. ALC 3, 4 and 5). Under the current UK agricultural system, it is unlikely that much grade 3 agricultural land will be used for bioenergy production, but here we provide an analysis of the potential contribution for that land should it be used to maximize the mitigation potential from BECCS.

4.1 | Centralized versus decentralized energy system

The future decentralization of the energy industry, anticipated by National Grid House (FES, 2018), represents a unique opportunity for encouraging the establishment of new domestic bioenergy supply chains, and the roll out of biomass CHP in the United Kingdom. Since generation from biomass is a thermal process, discharging high levels of heat stored in biomass, cogeneration of electricity and heat from biomass-only CHP is likely to be more efficient than electric-only power plants (Wang et al., 2014). Efficient CHP plants, however, tend to cost more than their less efficient counterparts, and given that the less efficient bioenergy stations consume more biomass, producing and sequestering more CO_2 from CCS, they may receive a larger revenue from providing this climate mitigation service (Mac Dowell & Fajardy, 2017). In addition, to limit transmission losses and costs of heat distribution, CHP stations have to be developed close to industrial and urban areas where heat demands are high and seasonal variations are low (Schmidt, Leduc, Dotzauer, Kindermann, & Schmid, 2010). This means that the optimum location for the development of CHP is likely to coincide with areas with low cultivation potentials, which reduces the potential scale of local bioenergy crop supply for the distributed CHP system. Furthermore, bioenergy crops are a distributed resource with a relatively low energy density, suggesting that generation from domestic biomass must be small scale to be economically and environmentally viable for both the centralized and DES. Given the above spatial constraints, in this study, we assumed the requirement for power stations to source domestic biomass feedstock from a radius of maximum 40 km. Thomas et al. (2013) and Ni et al. (2019) used a similar approach to assess the spatial bioenergy potential in England. Excluding overlaps between feedstock catchment areas, we found that the potential agricultural land available for bioenergy crops production, with low quality grade (i.e. ALC 4 and 5), is approximately 0.39 Mha for the CES, and 0.5 Mha across the DES. Our projections show that across GB, the land availability for sustainable bioenergy production is significantly lower than 1.4 Mha anticipated by ETI (2016). It is important to note that our results do not represent a scenario for biomass supply across GB; instead, they reflect a sustainable potential on the potential land suitable for power stations. If compared to the agricultural land currently used to produce biomass feedstock (i.e. 10 kha), or annual food crops for biofuels (i.e. 121 kha; BEIS, 2017; DEFRA, 2016), our projections represent a highly ambitious LUC scenario for the United Kingdom.

The level of LUC proposed here provides approximately 5.7 or 7.3 Mt_{DM}/year of biomass feedstock produced domestically across the biomass catchment areas of the centralized and decentralized system respectively. Considering the present levels of generation from domestically produced solid biomass (i.e. 1.6 Mt_{DM}/year; DECC, 2015a, 2015b), our estimates represent a significant increase in the domestic bioenergy market. However, in the past decade, the domestic energy produced from bioenergy has increased from 2.7% in 2010 to 6% in 2016 (BEIS, 2017). Therefore, it is plausible to expect that the effect of new governmental actions anticipated by Committee on Climate Change (2018) might be an important factor in encouraging new domestic biomass supply chains. Calculations show that the total energy generated from sustainable biomass-only feedstock ranges from 16 TWh/year in the centralized systems to 19 TWh/year in the distributed system. This will cover only 2.3% of the capacity of large power stations, and 11% of the local heat demand of CHP. However, it is arguably unfair to consider a single energy supply chain for the overall national grid, as the grid mix is, by definition, made up of a number of energy carriers and technologies with varying generation efficiencies. Previous projections from Committee on Climate Change (2018) show that the solid biomass generation potential for the United Kingdom could rise to 80 TWh/year (i.e. in their high biomass and natural peatland scenario). By including biomass from thinning, forest residues and bioenergy crops, ETI (2016) reported that potential domestic biomass generation could increase from 75 to 115 TWh/year across 1.4 Mha. If we include all the agricultural land of quality grade 3 in our scenarios, the potential biomass generation increases to 39 and 88 TWh/year in the centralized and distributed systems respectively. However, the conversion of agricultural land of quality grade 3 would displace agricultural production, leading to potential iLUC elsewhere.

4.2 | Environmental implications of bioenergy crop production

The LUC of agricultural land to bioenergy production has the potential to provide significant GHG emission savings and soil carbon sequestration (Albanito et al., 2016). We show that if all the marginal agricultural land within the catchment areas of the power stations is converted to bioenergy production, the net reduction in soil GHG emissions from LUC range from 9 to 11 Mt_{CO_2eq}/year in the centralized and distributed system. In 2016, agricultural soil emissions accounted for 24% of the total agricultural emissions in the United Kingdom (i.e. 46.5 Mt_{CO_2eq}/year; Committee on Climate Change, 2018). This suggests that a distributed supply of local and sustainable bioenergy production can provide an effective GHG mitigation strategy for the agricultural sector. In general, the cultivation of bioenergy crops in arable land provides higher environmental benefits compared to grassland. This is mostly due to the relatively higher anthropogenic *N* input rates and lower soil C content characterizing croplands. Across GB, the conversion of agricultural land to bioenergy would provide a net reduction in water pollution ranging from 20 to 53 $kg_{NO_3\text{-}N}$ ha^{-1} $year^{-1}$ on grassland and arable land respectively. In addition, we found a significant reduction in soil nitrate-N leaching to water, ranging from 112 to 120 $kt_{NO_3\text{-}N}$/year. Recently, Ni et al. (2019) reported similar nitrate leaching results from the conversion of winter wheat to *Miscanthus* in England. However, if unmanaged, the losses of SOC from LUC on grasslands can pose environmental concerns, as bioenergy crops are unlikely to counterbalance the losses of soil C in the initial establishing years (Behnke, David, & Voigt, 2012; Christian & Riche, 1998). Previous research has shown that the LUC effects on SOC stocks vary with quality of the soil being converted, with degraded soil offering more LUC benefits than rich soils (Cherubini et al., 2009; Crutzen, Mosier, Smith, & Winiwarter, 2008; Don et al., 2012; Gregory et al., 2018; Hastings et al., 2008, Hastings, Yeluripati, Hillier, & Smith, 2012; Richter, Agostini, Redmile-Gordon, White, & Goulding, 2015; Zatta, Clifton-Brown, Robson, Hastings, & Monti, 2014). Finally, the annual losses of SOC in former grassland were approximately 150 $kg_{SOC\text{-}C}$/ha, and by increasing the proportion of grasslands of better quality (i.e. ALC 3), SOC losses from LUC would decrease due to the higher soil C inputs from more productive bioenergy crop systems.

4.3 | Climate mitigation potential from BECCS

Taking into account all the spatial factors determining the local supply and demands of sustainable biomass feedstock, we found that approximately 1 Mha of agricultural land would be needed across GB to meet the climate target of 50 Mt_{CO_2eq}/year removed from BECCS by 2050 (Committee on Climate Change, 2016, 2018). The conversion of low-grade agricultural land achieves only 36% and 46% of the BECCS target from the centralized and distributed energy scenarios respectively. If we consider the centralized energy scenario, the above target gap can be closed by converting 0.59 Mha of additional agricultural land of grade 3 across GB, or by importing approximately 8 Mt_{DM}/year of solid biomass from forest systems. In the distributed energy scenarios, this gap could be filled by converting 0.49 Mha of agricultural land of grade 3, or by importing 6.6 Mt_{DM}/year of solid biomass from forest systems. As a reference to the above biomass import figures, in 2014, the United Kingdom imported around 3.1 Mt_{DM} of wood biomass in pellets from forest and processing residues from North America and Europe (DECC, 2015a). Note that, in our analysis, we assumed that the domestic biomass is locally supplied in bales, since below approximately 640 km, the transportation of biomass in bales is considered to be cheaper and to have a much lower overall GHG cost than pellets (Hastings, 2017).

In our BECCS scenarios, the emission intensity of bioenergy produced range from 20.6 to 27.4 g_{CO_2eq}/MJ in the centralized and DES respectively. Our results, therefore, are lower than the threshold set by the Renewable Obligation Scheme for solid biomass or biogas generating stations of 79.2 g_{CO_2eq}/MJ. Including bioenergy produced in agricultural land of grade 3, the generation intensity from biomass increases to 68.4 and 35.8 g_{CO_2eq}/MJ in the centralized and DES respectively. In that respect, by increasing the availability of land across the catchment areas of the power station, a higher proportion of cropland becomes available for CHP stations, which, by definition, are developed in areas with low cultivation potential.

In both the centralized and distributed energy scenarios, the Central and Southern regions of GB comprise approximately 80% of the potential CO_2 captured by the power stations (Figure 4). Considering that the geological storage fields in the United Kingdom are clustered in the Southern North Sea, Central North Sea and Northern North Sea, the most promising location for industrial CO_2 capture may be through the beachheads at Connah's Quay, Medway, Barmston and Redcar (ETI, 2016). In particular, the beachhead at Connah's Quay could be connected to the power plants in Wales, South West and West Midlands (i.e. 2.8 Mt_{CO_2}/year from CES or DES). The beachhead at Medway could be used for the Southern regions of South East, South West, London and Eastern (i.e. 3.3 Mt_{CO_2}/year from CES or 4.4 Mt_{CO_2}/year from DES). The beachhead at Barmston for the region of Yorkshire and the Humber and East Midlands (i.e. 1.7 Mt_{CO_2}/year from CES or 2.6 Mt_{CO_2}/year from DES). Finally, the beachhead at Redcar could be used to inject the CO_2 captured by the power stations in the region of North East and South of Scotland (i.e. 0.8 Mt_{CO_2}/year from CES or 2.3 Mt_{CO_2}/year from DES; Figure 4). Note that these CO_2 values correspond only to the mitigation potential from domestic bioenergy produced on sustainable land, and additional CO_2 needs to be produced and captured in order to meet the target of 50 Mt_{CO_2}/year from BECCS (see discussion above). The life-cycle unit cost of the CO_2 storage developments is difficult to assess due to the uncertainties of factors such as volume of CO_2 stored, and storage efficiency of depleted geological fields (ETI, 2016), but that is beyond the scope of this study. Other uncertainties involve the logistics for the deployment of onshore CO_2 transport infrastructures (i.e. pipelines or railways), which require cooperation between the major industrial CO_2 emitters for establishing CCS networks.

5 | CONCLUSIONS

We present a novel spatially explicit analysis for better quantification of the climate mitigation potential from BECCS across future energy scenarios in GB. By presenting two alternative energy pathway scenarios to maximize the decarbonization of the energy sector through BECCS, this study aims to provide a clearer understanding of land implications for domestic biomass feedstock supply, the potential power generation capacity from domestic biomass and the overall climate change implication of maximizing BECCS. The goal of 50 Mt_{CO_2eq}/year stored could only be achieved by 2050 by converting approximately 1 Mha of agricultural land to bioenergy crop production. This, however, is achieved through the use of approximately 0.5 Mha of agricultural land of good grade (ALC 3), which carries the risk of displacing food production. Assuming only sustainable land-use change to bioenergy production, the domestic supply of locally produced biomass feedstock ranges from 5.7 to 7.3 Mt_{DM}/year in the centralized and decentralized system, respectively, and up to 8 Mt_{DM}/year will need to be imported by the energy sector to meet the BECCS mitigation target of 50 Mt_{CO_2eq}/year. Our spatially explicit analysis could help to evaluate the climate trade-off between domestic bioenergy supply and biomass import possibilities, which could increase biogenic carbon emissions through iLUC effects elsewhere. In that respect, the outsourcing of pollution is a major risk factor for LUC policies, and the conversion of good quality agricultural land elsewhere for imported feedstock should be accounted for when estimating the climate mitigation potential of BECCS. In a fully decarbonized energy scenario, a decentralized energy systems would permit higher GHG mitigation potential than a centralized system. Considering, however, only the domestic biomass produced on low quality agricultural land, the emission intensity of the centralized system is lower than the decentralized system. In that respect, the emission intensity of the DES improves more rapidly than CES when the availability of biomass is not limited to domestic sustainable supplies. This suggests that if domestic bioenergy production is deployed to a level sufficient to realize economies of scale, both in the agricultural and energy sectors, distributed CHP generation can be an efficient strategy to decarbonize the energy sector. Future decarbonizing energy policies, however, should not incentivize electricity over heat, as this may encourage plant inefficiency (IEA, 2009).

Whether land is converted to bioenergy crops, remains under existing agricultural uses or undergoes change to other uses, depends on numerous factors, many of which are cross-cutting with wider sectors and have intractable uncertainties. For example, innovation in crop genotypes and agricultural practices, together with changing food, energy and carbon market conditions, could interact to change the decision-making context of the land-use system in unforeseen ways. Hence, we do not attempt to project which areas will or will not be converted. Instead, we determine the most effective use of land for maximizing bioenergy feedstock in the context of currently available land-use options. Considering all direct and indirect GHG emission savings associated with land-use change and biomass feedstock cultivation, the sustainable production of bioenergy across the catchment areas of the power stations can contribute to reduced agricultural GHG emission by 9 and 11 Mt_{CO_2eq}/year in the centralized and decentralized system respectively. This means that the conversion of 0.5 Mha of degraded agricultural land to biomass feedstock can contribute to achieving the target of net-zero soil emissions from the agricultural sector. How much GHG saving can be achieved from BECCS will depend on the speed of decarbonization and level of decentralization of power generation across GB. This study permits better understanding of the sustainable potential of BECCS, showing the spatial heterogeneity in the effects of LUC to bioenergy production on air, water and soil quality. Furthermore, as this study is spatially explicit, it also serves to identify the regional differences in the potential capture of CO_2 from CCS, providing the basis for the development of regional or national onshore CO_2 transport infrastructures, which will require large-scale cooperation between the major industrial CO_2 emitters.

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AUTHOR CONTRIBUTIONS

Author contributions: P.S., F.A. and A.H. conceived and designed the research; A.H. provided the bioenergy crop simulations; M.R. provided the simulations of net GHG emissions from land-use change in agricultural land; S.C.T. provided the energy demand simulations; F.A. performed the spatially explicit analysis; F.A. wrote the paper with contributions from P.S., N.F., A.H., P.L., M.R., DB, I.B., N.M., S.C.T., R.S. and M.M.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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