Received: 11 October 2019 | Revised: 22 March 2020 | Accepted: 19 April 2020

DOI: 10.1111/gcbb.12695

ORIGINAL RESEARCH

GLOBAL CHANGE BIOLOGY BIOENERGY WILEY

Bioenergy with Carbon Capture and Storage (BECCS): Finding the win–wins for energy, negative emissions and ecosystem services—size matters

Caspar Donnison[1,2] | **Robert A. Holland**[1] | **Astley Hastings**[3] | **Lindsay-Marie Armstrong**[4] | **Felix Eigenbrod**[5] | **Gail Taylor**[1,2]

[1]School of Biological Sciences, University of Southampton, Southampton, UK

[2]Department of Plant Sciences, University of California Davis, Davis, CA, USA

[3]Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen, UK

[4]School of Engineering, University of Southampton, Southampton, UK

[5]School of Geography and Environmental Science, University of Southampton, Southampton, UK

Correspondence
Gail Taylor, Department of Plant Sciences, University of California Davis, Davis, CA, 95616 USA.
Email: g.taylor@soton.ac.uk; gtaylor@ucdavis.edu

Funding information
Natural Environment Research Council, Grant/Award Number: NE/M019764/1

Abstract

Bioenergy with Carbon Capture and Storage (BECCS) features heavily in the energy scenarios designed to meet the Paris Agreement targets, but the models used to generate these scenarios do not address environmental and social implications of BECCS at the regional scale. We integrate ecosystem service values into a land-use optimization tool to determine the favourability of six potential UK locations for a 500 MW BECCS power plant operating on local biomass resources. Annually, each BECCS plant requires 2.33 Mt of biomass and generates 2.99 Mt CO_2 of negative emissions and 3.72 TWh of electricity. We make three important discoveries: (a) the impacts of BECCS on ecosystem services are spatially discrete, with the most favourable locations for UK BECCS identified at Drax and Easington, where net annual welfare values (from the basket of ecosystems services quantified) of £39 and £25 million were generated, respectively, with notably lower annual welfare values at Barrow (−£6 million) and Thames (£2 million); (b) larger BECCS deployment beyond 500 MW reduces net social welfare values, with a 1 GW BECCS plant at Drax generating a net annual welfare value of £19 million (a 50% decline compared with the 500 MW deployment), and a welfare loss at all other sites; (c) BECCS can be deployed to generate net welfare gains, but trade-offs and co-benefits between ecosystem services are highly site and context specific, and these landscape-scale, site-specific impacts should be central to future BECCS policy developments. For the United Kingdom, meeting the Paris Agreement targets through reliance on BECCS requires over 1 GW at each of the six locations considered here and is likely, therefore, to result in a significant welfare loss. This implies that an increased number of smaller BECCS deployments will be needed to ensure a win–win for energy, negative emissions and ecosystem services.

KEYWORDS

BECCS, bioenergy crops, carbon capture and storage, climate change, ecosystem service, land-use change, negative emissions, trade-offs

1 | INTRODUCTION

Average global temperatures are now one degree warmer than during the pre-industrial era (Allen et al., 2018) and despite commitments made by governments under the Paris Agreement (UNFCCC, 2016), the current trajectory is of increased emissions and further warming, with a prediction that global average temperatures could breach the 1.5°C average warming threshold as soon as 2030. There is, therefore, a shortfall between existing government's mitigation strategies and those required to meet the Paris Agreement targets of limiting warming to at most 2°C (Rogelj et al., 2018; United Nations Environment Programme, 2019). This has led to a growing interest in the development of technologies that can remove carbon from the atmosphere: negative emission technologies (NETs). The longer that necessary emission mitigation is delayed, the greater the need for NETs; in a recent IPCC Special Report, all scenarios consistent with limiting warming to 1.5°C, and most relating to 2°C, required carbon dioxide removal of some form (Rogelj et al., 2018), with Bioenergy with Carbon Capture and Storage (BECCS) featuring in most of these scenarios. Additionally, whilst the focus of NET deployment has been the second half of the 21st century, the longer greenhouse gas (GHG) emissions peak after 2020 the greater the risk that NETs will need to be deployment before 2050 (Obersteiner et al., 2018). Indeed, meeting the 1.5°C target without reliance upon BECCS requires very ambitious and immediate decarbonization (Rogelj et al., 2018).

Whilst BECCS could support the Paris Agreement targets and climate thresholds, there are concerns that the scale of future biomass feedstock and land-use demand may also have negative societal impacts and breach planetary ecological boundaries (Creutzig et al., 2015; Fuss et al., 2017; Heck, Gerten, Lucht, & Popp, 2018; Smith & Torn, 2013). The level of BECCS required to meet the Paris targets will be determined by the role of other NETs, such as afforestation, as well as the Shared Social Pathway, with a more sustainable societal pathway in relation to diet choice and resource use necessitating a smaller land-use and reduced risks to food production and sustainable development (IPCC, 2019). Scenarios consistent with limiting warming to 1.5 °C (with high overshoot) require an estimated median 6.8 Gt CO_2 removal per year by 2050 and median removal per year of 14.9 Gt CO_2 by 2100 (Rogelj et al., 2018). Shukla et al. (2019) estimate a BECCS potential ranging 0.4–11.3 Gt CO_2 by 2050. A recent systematic review concluded the sustainable potential of BECCS to be 0.5–5 Gt CO_2 removal per year by 2050 and that whilst this could increase by 2100, deployment of 10–20 Gt CO_2 removal per year could not be achieved without severe adverse effects (Fuss et al., 2017). Meeting the less stringent 2°C scenarios with BECCS still poses risks to ecological boundaries, with an estimated demand of 3.3 Gt C removal (equivalent to 12.1 Gt CO_2) per year by 2100—delivering circa 170 EJ—necessitating an estimated 380–700 M ha (equivalent to 7%–25% of global agricultural land) and water consumption equivalent to an additional 3% of the existing global demand (Smith et al., 2016). Life cycle analysis (LCA) has highlighted the human health impacts associated with BECCS, as a result of air pollution and ecotoxicity, particularly should fertilizer use rise with bioenergy crop production (Luderer et al., 2019).

In a review of studies, Slade, Bauen, and Gross (2014) found that in scenarios where bioenergy demand reaches 100–300 EJ, the range into which the Smith et al. 170 EJ scenario falls, non-agricultural land of 100–500 Mha is required at current biomass yields and where food demand is high, some deforestation may also be necessary to meet bioenergy demand. These findings were confirmed by Creutzig et al. (2015), identifying a sustainable global bioenergy potential of 100 EJ; however, these studies are all limited by the use of current yield data for bioenergy crops, which may be underestimating future yield improvements, by 10%–30% (Allwright & Taylor, 2016). Beringer, Lucht, and Schaphoff (2011) modelled bioenergy supply scenarios, estimating availability of 130–270 EJ by 2050. Dedicated bioenergy crops constitute 20%–60% of this total, requiring 142–454 Mha land, expanding cropland area by 10%–30% and approximately doubling irrigation demands. The land-use change (LUC) necessary to deliver BECCS could also cause severe biodiversity impacts (Hof et al., 2018).

The Paris Agreement requires Nationally Determined Contributions for emissions reductions from member states. In the United Kingdom, the Committee on Climate Change (CCC), an independent statutory body which advises the UK government on climate policy, has called for an immediate investment in Carbon Capture and Storage (CCS) technology in order to meet domestic emission targets (Committee on Climate Change, 2018b). BECCS deployment can be economically competitive by the 2030s (Committee on Climate Change, 2018a; UK Carbon Capture & Storage Cost Reduction Task Force, 2013) and CCC scenarios include up to 15 GW of BECCS capacity delivering 67 Mt (0.067 Gt) of CO_2 removal per year by 2050, whilst Daggash, Heuberger, and Mac Dowell (2019) model 8.5 GW of BECCS generation capacity capturing 51 Mt (0.051 Gt) of CO_2 per year in the United Kingdom by 2050. They estimate that meeting the UK 1.5°C target would require an estimated 15 GW of BECCS capacity. The necessity for early deployment of BECCS is reflected in these ambitious 2050 scenarios.

At the national level, the implementation of climate change policy is subject to various constraints. Adoption of BECCS will necessitate accepting environmental, social and economic costs relating to production, processing and transportation of biomass and transport and storage options for captured CO_2 (Baik et al., 2018). However, currently, these implications are not well understood or quantified, and this represents a research gap (Stoy et al., 2018). A recent analysis of BECCS in the United Kingdom explored the availability of marginal land to deliver sustainable BECCS power and deliver co-benefits (Albanito et al., 2019); however, no study to date integrates all of the environmental values of relevance to BECCS deployment. BECCS strategies must also be implemented within the context of other policy priorities for the environment, society and economy. In this study, we follow a similar framework to that used in the UK National Ecosystem Assessment (Bateman et al., 2014) which helped influence the 25 year Environment Plan, the central commitment of which is to ensure that UK natural capital is at least maintained over the next 25 years (HM Government, 2018). Here, we address a research gap by assessing the environmental demands, co-benefits and trade-offs, in addition to technology considerations associated with the spatial deployment of BECCS regionally, using the United Kingdom as a case study. We first develop a plausible location-specific scenario for large-scale BECCS power plants in the United Kingdom, and then generate land-use scenarios for domestic bioenergy crop resources using a land-use optimization tool, comparing the social and environmental implications at each location quantitatively.

2 | MATERIALS AND METHODS

2.1 | Identifying plausible BECCS sites and characteristics in the United Kingdom

BECCS locations and power station characteristics required for successful UK deployment were identified using a set of criteria that were quantified from available literature and other sources. These criteria were as follows.

2.1.1 | Deployment year

Commercially viable operation of BECCS has been identified as achievable by 2030 (Committee on Climate Change, 2018a; ETI, 2016b). An estimated 1.5 Gt CO_2e of North Sea storage capacity is estimated to be available by 2030, sufficient to service up to 10 GW of energy capacity (ETI, 2016b).

2.1.2 | Location

Captured CO_2 could be exported to North Sea storage sites using an offshore pipe network or initially via gas carrier vessels. The CO_2 export would be most likely from the east coast, adjacent to the North Sea for pipeline connections and where suitable port infrastructure already exists.

Inland pipeline networks are not only expensive but also require public acceptance and planning permission which can delay construction (Noothout et al., 2014). The initial deployment of BECCS would most likely draw upon existing infrastructure and minimize the costs and complexities of long-distance transport of either CO_2 or biomass feedstocks (Turner et al., 2018), favouring coastal locations. Minimizing onshore pipelines supports the deployment of BECCS power station 'clusters' within close proximity to existing port infrastructure, with favourable options identified at Thames, Barrow and Teeside (ETI, 2016b). In addition to these options, we consider BECCS deployment on existing energy infrastructure sites at Drax, the United Kingdom's largest power station (Drax, 2018); Peterhead, a gas power plant well connected to the North Sea and previously considered for CCS (BEIS, 2015); and Easington, a major gas terminal (see Figure 1).

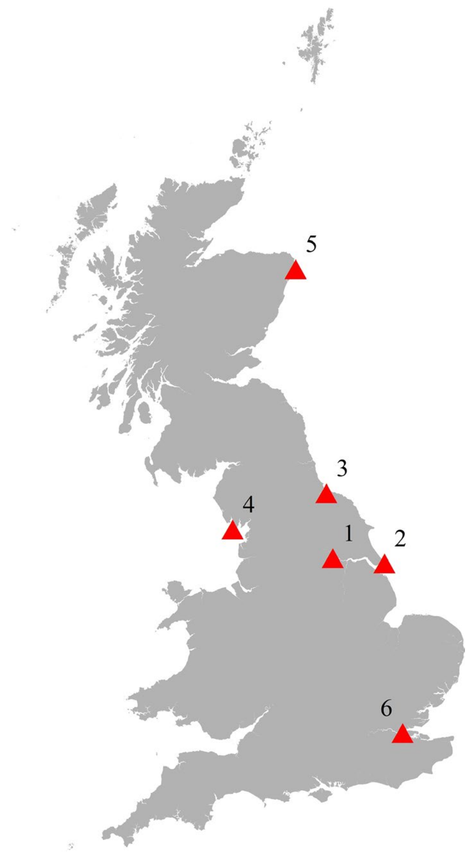

FIGURE 1 Bioenergy with Carbon Capture and Storage deployment options in the United Kingdom considered here: (1) Drax, site of existing large-scale bioenergy power station and previously proposed CCS project; (2) Easington; (3) Teeside, with CHP opportunity for industrial cluster and CCS infrastructure sharing opportunity with potential industrial CCS cluster; (4) Barrow; (5) Peterhead, site of previously proposed CCS project; (6) Thames, with CHP opportunity to London region

2.1.3 | CCS technology

There are currently three CCS technology options available to BECCS (Finney, Akram, Diego, Yang, & Pourkashanian, 2019):

- *Post-combustion capture* uses solvents (typically amines) to strip CO_2 from the flue gases. The CO_2 is separated by heating and then compressed for transportation;
- *Oxy-fuel combustion* supplies pure oxygen for the combustion process, producing a concentrated CO_2 stream which can be captured and then purified via condensing;
- *Pre-combustion capture* requires the conversion of the fuel into gaseous form, producing a mixture of hydrogen and CO_2.

In the fossil-fuel power sector, post-combustion capture can be retrofitted to existing power stations and is currently the only method used in commercial-scale projects (Bui et al., 2018), with a capture rate of around 90% (Adams & Mac Dowell, 2016). Oxy-fuel combustion has operated at demonstration facilities in the power sector (Carrasco, Grathwohl, Maier, Ruppert, & Scheffknecht, 2019) and can achieve a capture rate of 99% (Ekins et al., 2017), although further research is required to reduce efficiency penalties (Seddighi, Clough, Anthony, Hughes, & Lu, 2018). Pre-combustion capture through gasification has the potential to operate at lower efficiency penalties than post-combustion capture (Seddighi et al., 2018) and produces hydrogen which can offer flexibility through multiple energy vectors (Finney et al., 2019) as well as the storage of hydrogen during periods of low demand. However, at present, pre-combustion capture is relatively untested in the power sector and has yet to reach commercial status (Bui et al., 2018). Owing to its existing commercial operations and retrofitting potential, we assume that post-combustion capture will be used by the first BECCS systems.

2.1.4 | Unit size

For reasons of capital and running costs, and improved efficiencies, larger BECCS plant sizes of over 100 MW are favoured (Austin, 2017). Large bioenergy power stations are estimated to have greater thermal power efficiencies, at 30%–36% versus 25%–30% for smaller bioenergy plants (Koornneef et al., 2012). In terms of CO_2 transport costs, pipeline capacities of 10 Mt CO_2/year and above are estimated to deliver significant cost savings (Rubin, Davison, & Herzog, 2015) supporting the use of large-scale power stations. Koornneef et al. (2012) predict bioenergy plant sizes of around 500 MW to be likely in the near future. This is similar to Drax power station's proposed 448 MW CCS unit (Drax, 2015) and an assumed size of 500 MW in two recent BECCS studies (Daggash et al., 2019; Zhang et al., 2019). We assume power plants sized 500 MW in our modelling.

2.1.5 | Cooling system

Thermoelectric power plants have a high cooling demand, which can be provided by either a 'wet' cooling system using large quantities of water or a 'dry' cooling system using ambient air at a significantly higher financial and energetic cost (Kelly, 2006; European Commission, 2001). Operating power plants with CCS requires further cooling, and is estimated to double the water footprint of a 'wet' cooled power plant (Byers, Hall, & Amezaga, 2014; Byers et al., 2015; Zhai, Rubin, & Versteeg, 2011). At present, over 80% of UK thermoelectric power runs on wet cooling (Byers et al., 2014). However, future water scarcity and potential regional water risks of operating CCS in the United Kingdom have been highlighted (Byers et al., 2014), indicating that future thermoelectric power may require dry or hybrid cooling systems if it is not coastally located. Indeed, it is not certain that future water permits could be granted for large-scale BECCS power plants operating inland. We assume that the first BECCS plants would be located coastally or on tidal rivers, using the less costly wet cooling systems (see Data S1 for details).

2.1.6 | Plant thermal power efficiency

BECCS system efficiencies are expected to be considerably lower compared to non-CCS bioenergy power stations. Koornneef et al. (2012) estimate a BECCS power plant (using a Circulating Fluidized Bed) to operate at a thermal efficiency of 37%. Drax estimated that operating CCS at their power station would lead to a 24% fall in thermal efficiency, to 33% (Drax, 2015), whilst others have estimated similar overall declines of around 25% (Nicolas, Chen, Morris, Winchester, & Paltsev, 2017). Daggash et al. (2019) assume a thermal efficiency of 35%, based on a scenario of co-firing biomass with coal (Bui, Fajardy, & Dowell, 2017). We assume a thermal efficiency of 33% in our modelling (Tables 1 and 2).

2.1.7 | Feedstock demand

BECCS power plants sized 500 MW, operating at 85% capacity factor with a 33% thermal efficiency would generate an estimated 3.72 TWh/year and capture 2.99 Mt CO_2/year. This would require an estimated 2.33 Mt of fuel annually, based on an estimated 4.8 MWh per tonne of fuel (BEIS, 2014; Forest Research, 2019; see Data S1 for details).

TABLE 1 Key feedstock and technological assumptions for UK Bioenergy with Carbon Capture and Storage (BECCS) scenario based on literature review

Factor	Assumption	Reason	Source
Deployment year	2030	Estimate of first possible commercial BECCS deployment.	Drax (2015); Committee on Climate Change (2018a)
CCS technology	Post-combustion (amine)	This technology has the highest commercial readiness, alternatives are unlikely to be ready by 2030.	ETI (2016b); Bui et al., (2018)
Unit size	500 MW	Economies of scale in establishment and running costs and improved efficiencies of larger plant size.	Drax (2015); Koornneef et al. (2012)
Cooling system	Wet/hybrid	Wet (in coastal/tidal location) or hybrid (using freshwater inland).	Byers et al. (2014)
Water footprint versus non-CCS	Up to 100% higher	Double versus non-CCS under wet cooling or approx. 1.3 times higher under hybrid cooling system (operating at 35% dry 65% wet).	Byers et al. (2014)
Location	Coastal	Tidal or sea water opportunities for use in the cooling system, assuming future water constraints.	Byers et al. (2014)
		Close to port access for CO_2 export and storage sites.	ETI (2016b)
	Northeast England	Greatest regional water availability for power station water cooling needs and close to CO_2 storage sites.	Byers et al. (2014)
Thermal power efficiency	33%	Based on a post-combustion amine carbon capture with wet cooling system.	Daggash et al. (2019); Drax (2015); Nicolas et al. (2017); Rubin et al. (2015)
Domestic land demand	Domestic feedstocks are used only	Domestic bioenergy crop feedstock will be needed to contribute to a UK BECCS scenario.	Committee on Climate Change (2015); ETI (2016b); Committee on Climate Change (2018a)
Domestic feedstock	100 km radius of power plant	For fuel cost and emission reasons feedstock is sourced from within 100 km of the power plant.	Kumar and Sokhansanj (2007)
Feedstock type	Dedicated bioenergy crops	Demand necessitates fast-growing bioenergy crops, which can deliver some environmental benefits.	Committee on Climate Change (2018a)
Feedstock demand	2.33 Mt	Estimate based on power station thermal efficiency of 33% and load capacity factor of 85%, with bioenergy fuel of calorific value 4.8 kWh per kilogram.	Drax (2015); Forest Research (2019); BEIS (2014)

2.1.8 | Feedstock sourcing

Drax power station—the only large-scale biomass power station currently operating in the United Kingdom—imports the majority of its approximately 7 Mt annual wood fuel demand, enjoying the economies of scale of a well-developed international supply chain. This supply chain—which mostly utilizes sawmill waste wood and low-grade wood—has potential for expansion although it represents a limited biomass resource (Poyry, 2017). Dedicated bioenergy crops are expected to perform a major role under high future bioenergy demand (Beringer et al., 2011; Slade et al., 2014) and under BECCS deployment in the United Kingdom, including from domestic feedstocks (Committee on Climate Change, 2018a; ETI, 2016b). Only domestic feedstocks are used to satisfy power station demand in our scenario. At current averages yields of 12 t ha^{-1} year^{-1} (DEFRA, 2019a), meeting 2.33 Mt of feedstock for one 500 MW plant would equate to approximately 194,000 ha (0.194 Mha) of UK land, or approximately 2% of the 9.1 Mha of land technically available for bioenergy production (Lovett, Sünnenberg, & Dockerty, 2014).

2.1.9 | Domestic feedstock sourcing

Estimates of land available in the United Kingdom to grow bioenergy crops without increasing pressure on existing food security range from 0.45 to 1.4 Mha in studies that utilize low-grade agricultural land and also exclude land which has a high nature conservation value (Aylott, Casella, Farrall, & Taylor, 2010; Aylott et al., 2010; Clifton-Brown et al., 2017; Lovett et al., 2014; Wynn, Alves, & Carter, 2016). The CCC identify 1 Mha of land available for sustainably sourced biomass, which combined with imports could help deliver an estimated 22–67 Mt CO_2/year of negative emissions by 2050 (Committee on Climate Change, 2018a). The Energy Technologies Institute estimates that biomass imports could

TABLE 2 Ecosystem services used in modelling analysis

Ecosystem value	Metric(s)	Data	Model(s)	Value/ constraint	Source
Bioenergy crop yield	Yield (t ha^{-1} $year^{-1}$) and gross margin (£ ha^{-1} $year^{-1}$)	Soils, climate, bioenergy crop, species, costs and revenues	ForestGrowth-SRC; MiscanFor	Market values	Tallis et al. (2013); Hastings et al. (2009); Hastings et al. (2014)
Agricultural output	Gross margin (£ ha^{-1} $year^{-1}$)	Agricultural census farm data, climate	Agricultural model	Market values	Fezzi and Bateman (2011); Bateman, Harwood, Mace, et al. (2013)
Soil organic carbon	Soil carbon (t ha^{-1} $year^{-1}$)	Soils, climate, land-use	Estimation of Carbon in Organic Soils—Sequestration and Emissions (ECOSSE)	Non-market values	Smith et al. (2010)
Natural flood management	Land availability for bioenergy crops (hectares)	Flood zone land suitable for planting trees to mitigate flooding	Suitable land data integrated into model framework	Non-market values	Environment Agency (2015); TEEB
Water stress	'Traffic light' classification of land	Soils, climate, projected water abstractions	Water stress classification integrated into model framework	Constraint	Environment Agency (2013)
Landscape	Land availability for bioenergy crops (hectares)	Technical availability of land; availability of land according to 'naturalness' classification; National Parks; Areas of Outstanding Natural Beauty	Land availability data integrated into model framework	Constraint	Lovett et al. (2014); Environment Agency (2015); Jackson et al. (2008)

be combined with 1.4 Mha dedicated to bioenergy crops to deliver 55 Mt CO_2/year of negative emissions by the 2050s, mostly through increasing utilization of grasslands and excess crop production land (Wynn et al., 2016).

These estimates are national scale and distributed across the country; however, it is doubtful that it will be economically and logistically practical to fully utilize these resources for the concentrated demand of large-scale BECCS. The development of the Drax supply chain has also shown the desire for a centralized supply chain, as opposed to dealing with a large number of dispersed small suppliers. Whilst carbon costs of transport typically account for a small proportion of the overall lifecycle emissions of bioenergy crops (ETI, 2016b), maximizing the negative emissions of BECCS would also support sourcing domestic feedstock from a relatively small radius of the power plant, with the road haulage of non-densified bioenergy crops carrying relatively higher transport emissions (Hastings et al., 2017). Additionally, at present, there is no infrastructure for the densification of bioenergy feedstocks within the United Kingdom and we assume that this is unlikely to develop under an initial BECCS deployment. Depending on whether the biomass feedstock is in pellet, straw, or bale form, transporting 1 tonne 100 km with road haulage would emit 7.0–31.0 kg CO_2 eq. according to one study (Whittaker, Mortimer, Murphy, Hillier, & Smith, 2009), comparable to an equivalent 7.1–26.6 kg CO_2 eq. over the same 100 km distance in another study (Hastings et al., 2017). Here, we use the Hastings et al. data on carbon and economic cost estimates of harvest transport using bales (as used by Albanito et al., 2019), assuming that processing costs are constant at all locations and thus not considered further. We explore the implications of a 100 km (62 miles) distance constraint on the land available for a BECCS power plant supply chain.

2.1.10 | Feedstock type

In recognition of the poor GHG balance of first-generation food crops used in bioenergy chains (ETI, 2016a), bioenergy feedstocks considered here are second generation, non-food lignocellulosic crops of short rotation coppice (SRC) poplar or willow and *Miscanthus*. These crops are favoured for their superior yields on marginal land (Allwright & Taylor, 2016; Hastings et al., 2014), and enhanced impacts upon soil quality, pollination, water quality, regional cooling effects and other ecosystem services compared to first-generation food crops used for bioenergy (Georgescu, Lobell, & Field, 2011; Holland et al., 2015; McCalmont et al., 2015; Milner et al., 2016; Robertson et al., 2017). The United Kingdom at present has just 8,000 ha of dedicated bioenergy crops, but the barriers to expansion have been researched, particularly for *Miscanthus* where technical barriers have been deemed sufficiently met (Clifton-Brown et al., 2017). Nevertheless, the scale-up required under a BECCS scenario would be substantial.

We quantified changes in soil organic carbon (SOC) of LUC to bioenergy crops but not the total mitigation potential of agricultural GHG emissions associated with this LUC, usually determined by a whole LCA (Rowe et al., 2011), because this is complex, with outcomes depending on crop type (e.g. *Miscanthus* vs. SRC), the counterfactual land-use (arable, rotational grass, permanent grass or forestry), the length of rotation, the use of the biomass and because both positive and negative impacts of LUC to bioenergy cropping on GHG balance have been reported (Harris, Spake, & Taylor, 2015; McCalmont et al., 2015; Richards et al., 2017). Inconsistencies between empirical and modelled data are also apparent (Harris et al., 2017; Richards et al., 2017; Whitaker et al., 2018) and are highly dependent on LCA model inputs influenced by individual farm management practices (e.g. crop yield, crop type and nitrogen fertilizer application) and final use of biomass. Future research will focus on unravelling these complexities for overall impacts of UK BECCS deployment, using the optimization framework described here. However, their absence in this current study does not detract from the central findings on trade-offs and co-benefits.

2.2 | Ecosystem services and land-use scenarios

We assessed BECCS sustainability and environmental impacts using an economic ecosystem service assessment framework, similar to that described by Bateman, Harwood, Abson, et al. (2013). Ideally, stocks of natural capital and not just the flows would be quantified. However, there are difficulties with the existing methods of measuring natural capital, whilst quantifying ecosystem service flows is more thoroughly researched and can inform improved decision-making (Bateman, Harwood, Mace, et al., 2013). We analysed the impacts of LUC for four key environmental indicators, using ecosystem services of bioenergy yield (a provisioning service), agricultural output (a provisioning service), SOC (a regulating service) and flood mitigation (a regulating service). We used constraints for two further environmental indicators: water stress and landscape impact. Data limitations restricted us to this set of six indicators, although they reflect and extend previous research quantifying the ecosystem service impacts of bioenergy crops (Gissi, Gaglio, & Reho, 2016).

2.3 | Biomass productivity

Two process-based models were used to generate yield estimates of bioenergy crops at a 1×1 km^2 basis across the United Kingdom: the ForestGrowth-SRC model estimated yields for poplar and willow SRC (Tallis et al., 2013) and MiscanFor generated estimates for *Miscanthus* yields (Hastings, Clifton-Brown, Wattenbach, Mitchell, & Smith, 2009). Both models used soil data from the Harmonised Soil World Database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), at a 0.00833 degree resolution, and UKCP09 climate data from the UK Met Office, at a 25×25 km^2 resolution (Jenkins et al., 2009). The two models were also ground-truthed with yield data from trial sites across the United Kingdom (Hastings et al., 2014; Tallis et al., 2013). The models operate at a daily time step and we annualized yield outputs to calculate a decadal average for 2030, with yield maps published previously by Hastings et al. (2014). Yield estimates were used as well as establishment and annual costs from Hastings et al. (2017), an estimated market price of £75 per tonne—comparable to recent long-term prices offered by *Miscanthus* supplier Terravesta (Terravesta, 2013)—and a discount rate of 3.5%, as used by the UK government in policy appraisal (HM Treasury, 2018), to calculate the Net Present Value of the bioenergy crop over a 20 year horizon, and annual gross margin for bioenergy productivity within each 1×1 km^2 cell.

2.4 | Agricultural productivity

Estimates of the land available in the United Kingdom to grow bioenergy crops without increasing pressure on existing food security have been considered above, ranging from 0.45 to 1.4 Mha (Aylott et al., 2010; Clifton-Brown et al., 2017; Committee on Climate Change, 2018a; Lovett et al., 2014; Wynn et al., 2016). As has been noted, with these land availability estimates dispersed across the United Kingdom and, given the requirement for a spatially concentrated supply chain sourced from within 100 km of the power plant, a BECCS scenario may require the use of some agricultural land that would otherwise have been used in food production. It was important in the analysis to estimate the lost agricultural output of this LUC, to enable scenario comparison. In the United Kingdom National Ecosystem Assessment modelling, lost agricultural output—calculated as farm gross margin—was expressed as an 'opportunity cost' (Bateman, Harwood, Mace, et al., 2013). This 'opportunity cost' represents the value that the land could have generated if bioenergy crops were not grown on it. When bioenergy crops are grown on lower grade agricultural land (ALC 4-5), the opportunity cost is low. However, the feedstock demand of BECCS could necessitate the conversion of higher value land (ALC 1-3). Monetary opportunity cost estimates at a 1×1 km^2 resolution were obtained using gross margin estimates of an econometric agricultural value model (Fezzi & Bateman, 2011) which was used to perform similar analysis in the National Ecosystem Assessment modelling (Bateman et al., 2014).

This model uses historical data from the June Agricultural Census (DEFRA, 2019b) survey to determine land-use, soil, meteorological and historic price data.

2.5 | Carbon—SOC

Soil carbon (SOC) from growing bioenergy crops was taken from the Ecosystem and Land-use model (Pogson et al., 2016) which used the model Estimation of Carbon in Organic Soils—Sequestration and Emissions (Smith et al., 2010) to estimate spatially explicit soil carbon accumulation values at a 1 × 1 km^2 resolution across the United Kingdom (Pogson et al., 2016; Richards et al., 2017). We calculated the value of carbon mitigation through SOC, applying the Marginal Abatement Cost value published by the UK government (BEIS, 2018) and therefore firmly placed in the decision-making process.

2.6 | Transport costs

As noted, the United Kingdom lacks biomass densification infrastructure, and so for each 1 × 1 km^2 cell, transportation costs were estimated for the road haulage of harvested biomass in bale form to the power station. A weighting factor which accounts for deviation of the road network from the shortest path, termed road sinuosity, was applied to the transport costs. To calculate this, for each road segment of the UK road network, the ratio was calculated between the length of the road segment and the shortest path between the two end points of the road segment. These ratios were then used to calculate road sinuosity values at a 1 × 1 km^2 basis. For each of the BECCS locations of interest, the average road sinuosity value for that location was calculated by averaging the road sinuosity values of all of the 1 × 1 km^2 cells within the 100 km radius region. We added to this financial cost a monetized carbon cost of transport, using estimates of the carbon cost of biomass transport (Hastings et al., 2017) and applying the UK government Marginal Abatement Cost.

2.7 | Hazard protection—Natural flood management

Flooding events are expected to become more prevalent and damaging in the United Kingdom as a consequence of climate change (Environment Agency, 2018a; Hirabayashi et al., 2013; Hoegh-Guldberg et al., 2018; IPCC, 2012) and significant sums of money are already spent on flood mitigation projects. There is increasing interest in natural solutions to flood protection, including the use of bioenergy crops. Of the limited existing research into the potential for bioenergy crops to provide flood mitigation, there are grounds for some reasonable assumptions. Bioenergy crops are described as operating like a 'green leaky dam', slowing the flow of flood water as well as retaining more water than grassland or other crops (Rose & Zdenka, 2015), and their high canopy interception—comparable to deciduous forestry—has already been identified as a potential flood mitigation benefit (Holder, McCalmont, McNamara, Rowe, & Donnison, 2018). Bioenergy crops also escape flood damage that could destroy other crops; both poplar and willow are adapted to riparian zones and able to tolerate significant flooding.

We used an Environment Agency spatial data layer of the best locations to plant trees for the mitigation of flooding (Hankin et al., 2018). These data—in polygon format—were used to calculate the number of hectares available for flood mitigation in each 1 × 1 km^2 grid cell. We next searched The Economics of Ecosystems and Biodiversity (TEEB) database for published studies estimating the monetized mitigation benefits of natural flood management. The five studies used gave us a range of flood mitigation values from £14 to £1,525 ha^{-1} year^{-1} (Anielski & Wilson, 2005; Dubgaard, Kallesøe, Petersen, & Ladenburg, 2002; Environment Agency, 2009; Ledoux, 2004; Leschine, Wellman, & Green, 1997). Acknowledging that more people are affected by flooding events taking place in areas of high population, we weighted the flood mitigation values with the 2011 Census population density data set for the United Kingdom (Eigenbrod et al., 2011). To do this, we took the log population density data at the 1 × 1 km^2 basis from the 2011 census. We calculated the linear equation between population and the TEEB values, with the intercept as the lowest TEEB value. This population-weighted value was combined with the spatial data set of flood management locations to provide a monetary value per hectare of bioenergy crops planted in each 1 × 1 km^2 cell.

2.8 | Water—Water stress index

Second-generation bioenergy crops are estimated to use water more efficiently than arable crops (Berndes, 2008) but also to use more water in absolute terms, owing to a higher evapotranspiration rate (Le, Kumar, & Drewry, 2011) and higher canopy interception (Finch & Riche, 2010). However, increased canopy interception occurs during the higher rainfall of winter months which can support flood mitigation (Holder et al., 2018). Bioenergy crops are also found to have reduced run-off and more water storage compared to arable crops (Le et al., 2011; Stephens & Hess, 2001). Assessing the impact of bioenergy crop planting on water resources is therefore complex and may be catchment specific. Bioenergy crops can provide flood mitigation benefits, or risk water shortages, depending on the local water resources. Our BECCS scenario requires clustering bioenergy crops around power stations which could pose risks for local water resources; a study of *Miscanthus* cultivation in the United States estimated that a high density of planting would have a severe impact on the hydrological cycle (Vanlooke, Bernacchi, & Twine, 2010). Tools like the land-surface JULES model (Best, Pryor, Clark, Rooney, & Essery, 2011) are helping to estimate water consumption of bioenergy crops (Oliver, Blyth, Taylor, & Finch, 2015). However, there is future uncertainty regarding how water demand will change in a context of growing pressures on water resources from climate change, a rising population and economic development (Committee on Climate Change, 2016). Owing to these complexities, and a lack of spatially explicit data resolved at the level required, we did not quantify water use in this analysis. Although this is an area where further study is warranted, here we applied a precautionary approach, using a well-established water stress classification metric from the Environment Agency to apply a constraint in the model, excluding land areas estimated to be water stressed, defined as those where the water flow rate is 50% or more below the long-term rate (Environment Agency, 2013). We re-scaled the water stress data layer (polygon format) to ascribe a water stress value to each 1×1 km^2 grid cell. Each grid cell's water stress value represented the value of the polygon that covered the majority of the area of that cell. Accounting for the possible overlap of water-stressed land with areas of flood risk, we decided the model should permit bioenergy crop planting on land cells classed as water-stressed if at least 5 ha of the cell held flood mitigation opportunities.

2.9 | Physical constraints

We used a set of physical constraint maps from previous modelling research (Lovett et al., 2014) of designated areas, natural habitats and woodland, as well as a number of physical constraints: slope > 15%; peat (soil C > 30%); urban areas; roads; rivers; parks; and scheduled monuments/world heritage sites. These exclusions were run at a 100×100 m^2 grid cell basis in Lovett et al. (2014) and we used this to calculate the proportion of each 1×1 km^2 cell likely to be available for bioenergy crop conversion.

2.10 | Landscape constraints

In addition to the physical constraints from Lovett et al. (2014), we applied a landscape constraint. Survey and interview evidence suggest that the visual impact of bioenergy crops is not a concern for the public (Upham & Shackley, 2006) and that these crops can fit well into a UK landscape (Bell & McIntosh, 2001; Dockerty, Appleton & Lovett, 2012). However, bioenergy crops are currently sparsely deployed in the United Kingdom and as crop density increases in the landscape, there may be a threshold over which the dominance of bioenergy crop stands begin to drive visual disamenity (Dockerty et al., 2012; Skärbäck & Becht, 2005). This is likely to depend on the context of the specific landscape in which bioenergy crops are grown as well as crop type, with coppice trees providing a different visual landscape to *Miscanthus*, which appears like an annual row crop as opposed to a wooded landscape. Acknowledging this, as well as evidence that the human experience of a landscape is positively connected to its perceived 'naturalness' (Ode, Fry, Tveit, Messager, & Miller, 2009; Purcell & Lamb, 1998), we used the results of a survey of perceived naturalness of different land cover types (Jackson et al., 2008), as previously demonstrated in Lovett et al. (2014). We adopt a precautionary principle constraining planting to outside those regions with a high level of naturalness (a naturalness 'score' of over 85) where bioenergy crops are most likely to deliver a visual disamenity. Acknowledging the importance of National Parks and Areas of Outstanding Natural Beauty, we applied a more stringent naturalness score threshold of 65 and above in these regions.

2.11 | Market cost and welfare value

From the ecosystem service data layers, two new data layers were generated, both at the 1×1 km^2 grid basis: a 'market cost' value was calculated from the agricultural value, bioenergy crop value and transport costs data, reflecting the existing market costs of growing bioenergy crops and delivering them to the power station, and a 'welfare value' was calculated which integrated the market cost with values for the non-market services of SOC and flood mitigation, as well as the carbon cost of transport.

2.12 | Land-use spatial optimization

GIS software ArcMap 10.6 was used to prepare all data to the same 1×1 km^2 resolution across the United Kingdom. These data layers were downloaded from ArcMap as data matrices, resulting in a combined data matrix whereby each 1×1 km^2 cell in the United Kingdom was ascribed values for all of the above indicators. We clipped the matrix to each BECCS location option by applying the 100 km radius constraint. The 'greedy' optimization algorithm (Cormen, Leiserson, Rivest, & Stein, 1990) was applied to each of the location matrices to optimally select land, as demonstrated in previous ecosystem service research (Keller, Fournier, & Fox, 2015). Two separate greedy optimizations were run in Matlab: one optimized bioenergy crop land-use based on minimizing market costs, and the second optimized land-use based on maximizing welfare values, subject to the additional water stress and landscape constraints (modelling code is available upon request). We ran the welfare optimization five times, once with all of the environmental values integrated, and once for each of the environmental values in isolation. Depending on which values the greedy algorithm maximized, the optimization first selected the 1×1 km^2 cell of the highest value for bioenergy crop deployment, and then the cell of the second highest value, and so on until the demand total for a 500 MW BECCS power plant was reached. The market and welfare optimizations were also run for a 2×500 MW (1 GW) BECCS power plant which would require an estimated doubling (4.65 Mt) of the biomass demanded by a 500 MW plant. Running the optimization at 1 GW allowed us to estimate the land-use and environmental implications of a higher BECCS deployment.

3 | RESULTS

The degree to which the optimizations of each of the individual environmental values in isolation led to a different land-use scenario relative to the market-based scenario is shown for five of the BECCS location sites in Figure 2. Incomplete flood mitigation and water stress data availability prevented a full analysis of the Peterhead location. The greatest difference in land-use was seen between the flood management values and market values optimizations. The welfare optimization, which integrated all the environmental values, differed from the market optimization in terms of both land-use and environmental impact (Table 3). As shown in Table 3, in each of the BECCS location options, the welfare optimization led to an increase in land-use relative to the market optimization, a decrease in agricultural value, a decrease in water-stressed land-use and an increase in stored carbon and flood mitigation. Under the welfare optimization, developing a 500 MW BECCS power plant generated the highest estimated annual social values at the Drax and Easington sites, £39 and £25 million respectively. Lower annual welfare values were exhibited at Thames (£4 million) and Teeside (£2 million), and a welfare loss of £6 million was estimated at Barrow.

Comparisons of the environmental impacts that resulted from both the market and welfare optimizations shown in Table 3 were represented in the form of radar charts (Figure 3).

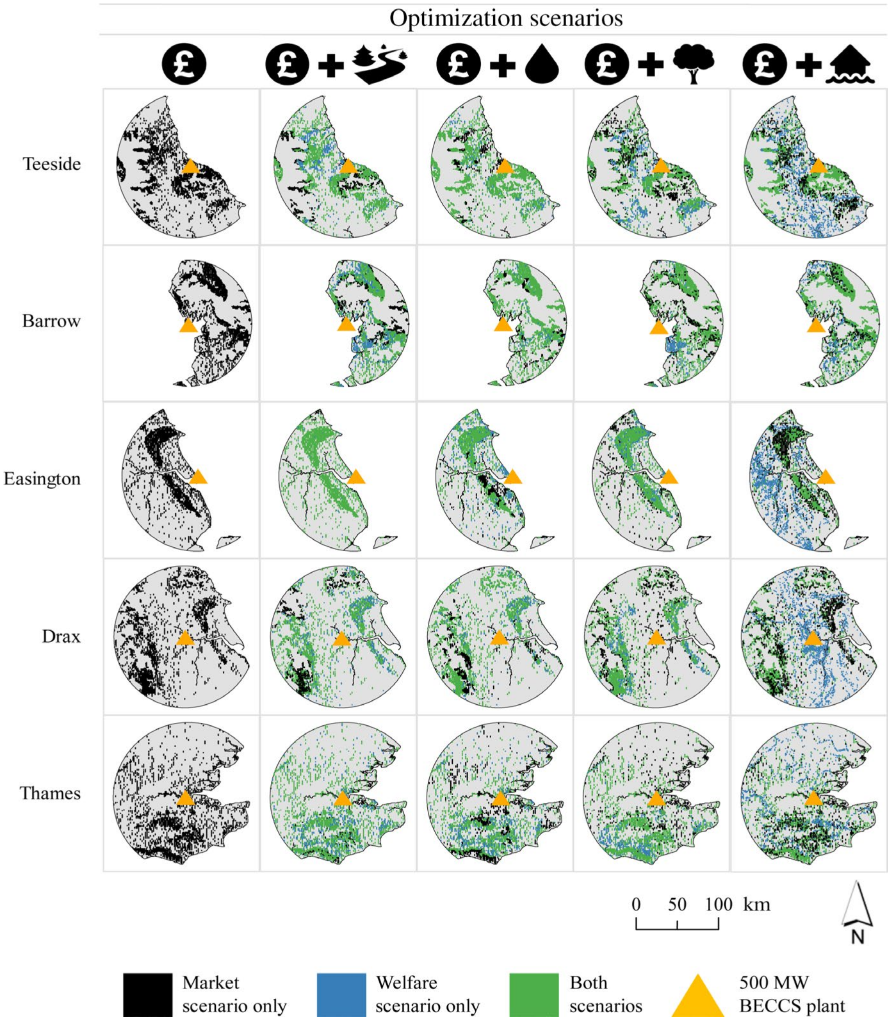

FIGURE 2 Contrasting land-use options for bioenergy crop planting under a 500 MW Bioenergy with Carbon Capture and Storage power plant scenario at five sites across the United Kingdom: Teeside, Barrow, Easington, Drax and Thames. Five separate optimizations are displayed for each site. The first column represents land-use under the market (agricultural and bioenergy crop values) [£] optimization, the second column optimizes market values subject to the landscape constraint [], the third column optimizes market values subject to the water stress constraint [], the fourth column optimizes market and carbon [] values together and the fifth column optimizes market and flood management [] values together. Note: points in each panel represent bioenergy crop planting in a 1×1 km^2 cell, but the number of hectares of bioenergy crops planted in each 1×1 km^2 cell varies, depending on the land determined available according to the land-use constraints applied. Grey is the fill colour

TABLE 3 Comparisons between the resulting values of the market and welfare optimizations at each of the five location options, under a 500 MW Bioenergy with Carbon Capture and Storage scenario. For each location, the two scenarios are compared based on the total land-use, the land-use on water-stressed land, the change in value, in £ million (£ m) in terms of agricultural output, soil carbon, flood protection, as well as the market cost and welfare value

Scenario (500 MW)	Land-use (ha)	Water stress (ha)	Agriculture value change (£ m)	Carbon value change (£ m)	Flood protection change (£ m)	Market value change (£ m)	Welfare value change (£ m)
Thames market	187,887	46,079	−53	14	7	−25	−4
Thames welfare	189,395	0	−62	15	21	−34	2
Drax market	165,984	24,565	−48	9	4	−17	−5
Drax welfare	187,756	817	−64	9	65	−34	39
Easington market	180,755	32,366	−58	9	6	−29	−14
Easington welfare	194,071	1,110	−69	8	59	−41	25
Barrow market	140,169	8,928	−49	7	4	−20	−9
Barrow welfare	143,275	0	−59	7	4	−26	−6
Teeside market	171,571	17,416	−49	6	4	−20	−9
Teeside welfare	177,429	0	−59	8	25	−29	4

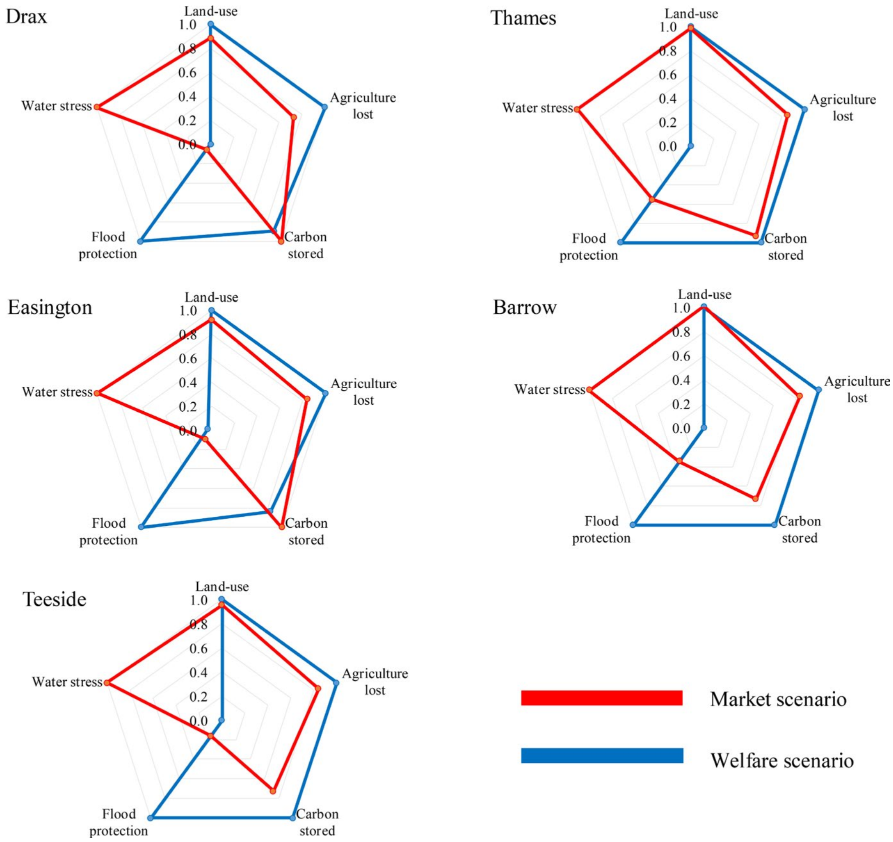

FIGURE 3 The change in environmental indicators resulting from each of the two optimizations: the market (agricultural and bioenergy crop values) optimization and the welfare optimization (incorporating landscape, water stress, carbon, and flood management values). 'Land-use' refers to the land-use of each scenario; 'Agriculture lost' refers to the lost agricultural output of each scenario; 'Carbon stored' refers to the value of soil organic carbon accumulation under each scenario; 'Flood protection' refers to the value of flood mitigation under each scenario; and 'Water stress' refers to the quantity of water-stressed land under each scenario. Values were standardized to 1 in order to compare different metrics on the same graph

Interaction between those environmental values which could be quantified was explored by calculating Spearman's correlation coefficients. These were calculated for pairs of ecosystem services present at each of the BECCS location options in order to establish whether a positive correlation or trade-off (a negative correlation) relationship existed

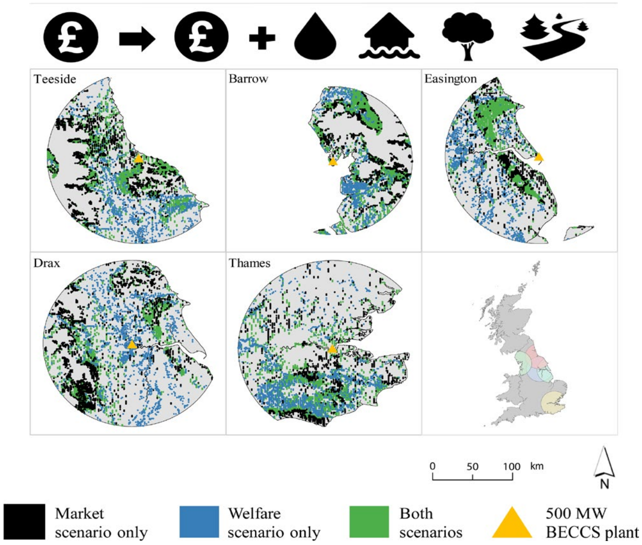

FIGURE 4 Contrasting land-use options for bioenergy crop planting under a 500 MW Bioenergy with Carbon Capture and Storage power plant scenario for five sites across the United Kingdom: Teeside, Barrow, Easington, Drax and Thames. Each panel shows the difference between the market optimization and the welfare optimization (incorporating environmental values). Note: points in each panel represent bioenergy crop planting in a 1×1 km^2 cell, but the number of hectares of bioenergy crops planted in each 1×1 km^2 cell varies, depending on the land determined available according to the land-use constraints applied. Grey is the fill colour

between the ecosystem services. As shown in Figure 4, the Spearman's correlation coefficients showed a moderately strong relationship between bioenergy yield and SOC in two of the five sites. However, no or only very weak relationships were shown between all other ecosystem pairs (Figure 4).

4 | DISCUSSION AND CONCLUSIONS

We developed a land-use optimization tool which integrated environmental and social values and generated land-use scenarios for site-specific deployment of BECCS in the United Kingdom. Our results highlight the importance of both scale and location in determining the social and environmental trade-offs and co-benefits resulting from regional BECCS deployment. Although recent BECCS research has provided detail of some of these impacts (Cavalett, Slettmo, & Cherubini, 2018; Luderer et al., 2019; Smith et al., 2019), these studies are limited in not being spatially resolved to provide detail on where trade-offs or co-benefits may occur. Other studies have addressed the important questions relating to the location and size of the bioenergy resource potential for BECCS, but do not consider the location of BECCS infrastructure regionally (Daioglou, Doelman, Wicke, Faaij, & van Vuuren, 2019; Muri, 2018). Several regional studies have considered location options of BECCS power stations and bioenergy resources, but without integrating associated social and environmental impacts (Albanito et al., 2019; Zhang et al., 2019). Thus, our research extends current understanding by exploring trade-offs, defined here as 'when an increase in one service or benefit brings about a decrease in another service or benefit'.

The results of this study show that integrating environmental values into land-use decision-making resulted in a higher net welfare value compared to a purely market-based decision (Table 3), as reflected in previous research for other LUC (Bateman, Harwood, Mace, et al., 2013), but reported here for the first time when considering the large-scale deployment of BECCS. The benefits for 500 MW plants largely disappeared, however, when the capacity of BECCS at each site was increased to 1 GW. It was also found that the net social value of BECCS was site-specific, varying notably between the locations studied (Table 3). Each site differed with respect to the distribution and magnitude of environmental services present (Figure 5).

The Drax site, followed by Easington, is the best location for a first BECCS deployment in the United Kingdom. The high welfare values at these two sites were chiefly driven by the valuable opportunities of growing bioenergy crops to provide flood mitigation, reflected in the high economic costs of flooding in the Yorkshire and Humber region (Mendoza-Tinoco, Guan, Zeng, Xia, & Serrano, 2017). The two sites, especially Drax, also benefitted from greater land area available under the 100 km distance constraint. These two advantages to the Drax and Easington sites explained why welfare value remained relatively high as BECCS deployment increased (Figure 6), while valuable land-use opportunities were exhausted more quickly as BECCS deployment increased at the three other sites. Welfare values fell sharpest at the Barrow site, generating a net social cost above 350 MW of BECCS deployment (Figure 6), where flood mitigation and soil carbon sequestration opportunities were the most limited of all sites. This suggests that developing BECCS in some locations, such as Barrow, would generate greater social costs locally or require a high dependency upon biomass feedstock imports from outside the region. The importance of integrating environmental impacts into energy scenarios has been highlighted in previous studies (Holland et al., 2016; Hooper et al., 2018) and the impact of bioenergy-driven LUC on ecosystem services and biodiversity has also been reported (Hof et al., 2018; Milner et al., 2016; Tarr et al., 2017), but no previous study has integrated these concepts into a consideration of BECCS.

Only one ecosystem service pair showed a robust correlation across more than one of the sites. The relationships between ecosystem services studied here and the spatial pattern of their provision are therefore complex, as has been noted previously when considering bioenergy deployment and LUC

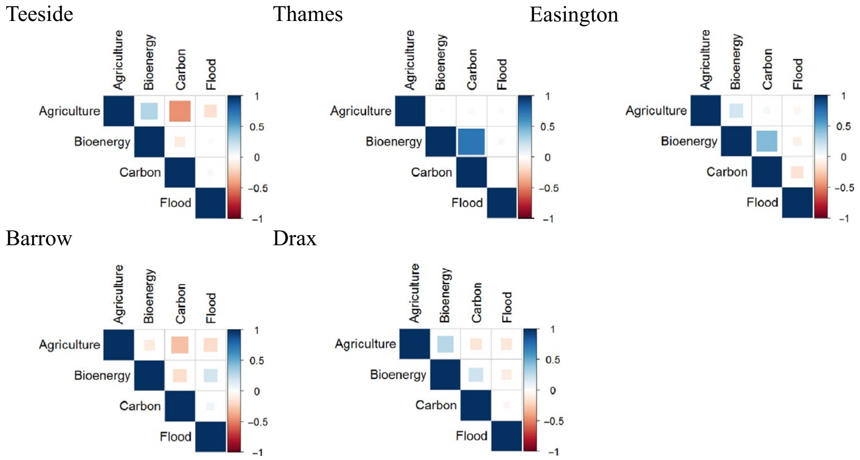

FIGURE 5 Spearman's correlation coefficients between the quantifiable ecosystem services used in the analysis, shown as a heat map. We used values for lost agricultural production ('Agriculture'), value of soil organic carbon accumulation ('Carbon'), bioenergy production ('Bioenergy') and value of flood management ('Flood'). Blue and red boxes indicate statistically significant co-benefit and trade-offs, respectively, whilst the size of square indicates the correlation magnitude. See Data S1 for *p*-values of all pair-wise comparisons tested

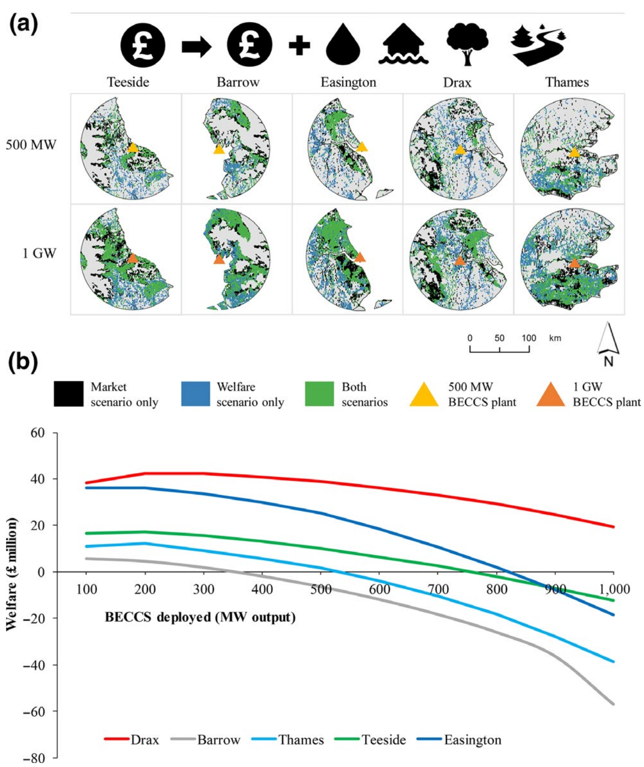

FIGURE 6 (a) Land-use for the market and welfare optimization scenarios at Teeside, Barrow, Easington, Drax and Thames, under a Bioenergy with Carbon Capture and Storage (BECCS) deployment of 500 MW (top row), and a doubled BECCS deployment of 1 GW (bottom row). Note: points in each panel represent bioenergy crop planting in a 1×1 km^2 cell, but the number of hectares of bioenergy crops planted in each 1×1 km^2 cell varies, depending on the land determined available according to the land-use constraints applied. Grey is the fill colour. (b) Welfare values (£ m) resulting from a BECCS deployment under the welfare optimization scenario at each of the five locations, and a range of BECCS deployment levels, measured in terms of MW output, from 100 to 1,000 MW (1 GW)

(Gissi et al., 2016; Milner et al., 2016). This suggests that developing a policy framework to optimize for multiple ecosystem services will be challenging, with no existing framework available, emphasizing the importance of understanding the site-specific considerations for BECCS deployment.

Integrated Assessment Models (IAMs) select high levels of BECCS in 1.5°C and 2°C emission pathways, with the resulting scenarios necessitating an unprecedented scale of land-use required for bioenergy crops (Smith et al., 2016; Vaughan et al., 2018). These models optimize based on financial costs (Fuss et al., 2014; Mander, Anderson, Larkin, Gough, & Vaughan, 2017; Smith et al., 2016) and lack spatial analysis of environmental impacts. The feasibility of IAM scenarios should be assessed through their integration with spatially explicit environmental models and our study provides a step towards achieving a more holistic appraisal of BECCS technology, providing the first conceptual framework which integrates environmental and social impacts at a granular and site-specific level. Our results strongly suggest that sustainable limits to BECCS deployment exist, addressing an outstanding area of controversy that surrounds the reliance upon biomass feedstock for negative emissions (Creutzig et al., 2015; Fuss et al., 2017; Heck et al., 2018; Smith & Torn, 2013). We have shown that such a holistic appraisal can be quantitative, as is likely to be required by future land-use decision-making tools (UK National Ecosystem Assessment, 2011).

We conducted sensitivity analyses testing the impact of increased bioenergy crop yield and a greater supply radius of 200 km. The sites of highest welfare values remained the most attractive under these scenarios, with the increased yield scenario reducing land-use and market costs and the increased supply radius scenario increasing welfare values across the sites (see Data S1 for these scenario results and further discussion). A different approach to our scenario of large-scale BECCS deployment in the United Kingdom could be to deploy a greater number of smaller BECCS power plants, feeding into hub locations for CO_2 export. Such a strategy could make better use of the spatially dispersed low value agricultural land in the United Kingdom. There are sizeable opportunities to grow bioenergy crops in the United Kingdom (Aylott et al., 2010; Renewable Fuels Agency, 2008), whilst still delivering other environmental services (Holland et al., 2015). However, as highlighted earlier, the high capital costs of BECCS infrastructure and the economies of scale and improved efficiencies of larger power plants make this route unlikely until technological and financial barriers are removed.

To deliver the UK Committee on Climate Change BECCS scenario of 67 Mt (0.067 Gt) of CO_2 removal per year by 2050 would require approximately 22 × 500 MW power stations across the United Kingdom, and 52 Mt of bioenergy feedstock. This level of feedstock demand is notably above previously discussed estimates of sustainable bioenergy supply in the United Kingdom, and would require approximately half of the 9.1 Mha of UK land technically available for bioenergy crops. Deploying this level of BECCS in the United Kingdom is not modelled in our analysis and would require a combination of United Kingdom and imported bioenergy feedstocks, for which there are associated financial (Daggash et al., 2019) and environmental costs (European Commission, 2016).

Although there has been significant scientific progress since the completion of the 2005 Millennium Ecosystem Assessment (Millennium Ecosystem Assessment, 2005), designing policies that meet multiple energy and environmental objectives in line with the Sustainable Development Goals (Fuso Nerini et al., 2017; United Nations, 2015) such as in natural capital valuation, requires further progress to achieve full monetary valuation of ecosystem services, as highlighted in recent reviews (Mishra et al., 2019; Niquisse & Cabral, 2017). Policymakers can currently incorporate a limited but important set of values into the decision-making process, and across the globe, there are now over 550 payments for ecosystem service programmes totalling an estimated \$36–42 billion of annual payments (Salzman, Bennett, Carroll, Goldstein, & Jenkins, 2018). The UK government has announced that the provision of environmental services will be supported through redirecting existing farm subsidy payments, following the United Kingdom's departure from the EU's Common Agricultural Policy (HM Government, 2018). This could facilitate farm diversification as well as supporting bioenergy crop planting on land where environmental service co-benefits can be delivered (Committee on Climate Change, 2018a).

In the analysis here, bioenergy crop yields and soil carbon are amongst those services currently best mapped and quantified (Gissi et al., 2016; Milner et al., 2016), whilst our understanding of other ecosystem services is more limited, exposing a significant research gap in the development of realistic scenarios and modelling frameworks for sustainable deployment of BECCS. For example, flood mitigation benefits exist (Rose & Zdenka, 2015) but placing a value on them is difficult, with limited research in this area to date. The flood mitigation values used in our analysis were based on previous studies of the benefits of natural flood management, reflecting the financial costs of flooding. The Environment Agency estimated the costs of the 2015–2016 winter flooding in England at £1.6 billion (Environmental Agency, 2018b) whilst a recent modelling exercise estimated that flood defences reduce river flooding damages by £1.1 billion annually in the United Kingdom (Risk Management Solutions, 2019). Flood risk is also spatially explicit and the regional impacts can be severe, with floods in 2007 estimated to have cost the Yorkshire and Humber region £2.7 billion in losses (Mendoza-Tinoco et al., 2017), highlighting the need to integrate these environmental impacts into energy scenarios.

It is much harder to quantify ecosystem services values for cultural and aesthetic value and there is a case that these values cannot be reflected by any price or quantity (McCauley, 2006; Small, Munday, & Durance, 2017). Their incorporation into a decision-making framework is therefore both challenging and controversial. Despite this, the framework that has been used here shows the notable changes that result from incorporating ecosystem services that can be adequately quantified at present.

The past few years have seen an increasing sense of urgency with respect to the action required to meet the Paris Agreement targets. We have shown how the scale of BECCS deployed and its location determines environmental and social impact. In choosing BECCS as a means of achieving mitigation targets, it will be important for policymakers to understand the spatial and environmental considerations associated with BECCS at the regional scale if they are not to jeopardize public support and other policy goals.

ACKNOWLEDGEMENTS

This work was supported by the NERC-funded UK Energy Research Centre, by the NERC project Addressing the Valuation of Energy and Nature Together (ADVENT, NE/M019764/1) and by The University of California, Davis with CD the recipient of a NERC PhD studentship (1790094). It also contributed to the NERC FAB-GGR project (NE/M019691/1).

ORCID

Caspar Donnison https://orcid.org/0000-0001-6052-7339
Astley Hastings https://orcid.org/0000-0001-9863-7613
Lindsay-Marie Armstrong https://orcid.org/0000-0002-5491-3353

Felix Eigenbrod https://orcid.org/0000-0001-8982-824X
Gail Taylor https://orcid.org/0000-0001-8470-6390

REFERENCES

Adams, T., & Mac Dowell, N. (2016). Off-design point modelling of a 420 MW CCGT power plant integrated with an amine-based post-combustion CO_2 capture and compression process. *Applied Energy*, *178*, 681–702. https://doi.org/10.1016/j.apenergy.2016.06.087

Albanito, F., Hastings, A., Fitton, N., Richards, M., Martin, M., Mac Dowell, N., … Smith, P. (2019). Mitigation potential and environmental impact of centralized versus distributed BECCS with domestic biomass production in Great Britain. *GCB Bioenergy*, *11*, 1234–1252. https://doi.org/10.1111/gcbb.12630

Allen, . R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., … Zickfield, K. (2018). Framing and context. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, … T. Waterfield (Eds.), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. In press. Retrieved from https://www.ipcc.ch/sr15/chapter/chapter-1/

Allwright, M. R., & Taylor, G. (2016). Molecular breeding for improved second generation bioenergy crops. *Trends in Plant Science*, *21*(1), 43–54. https://doi.org/10.1016/j.tplants.2015.10.002

Anielski, M., & Wilson, S. (2005). *Counting Canada's natural capital: Assessing the real value of Canada's boreal ecosystems*. Retrieved from https://www.cbd.int/financial/values/canada-countcapital.pdf

Austin, A. (2017). Size matters. Retrieved from Biomass Magazine website http://biomassmagazine.com/articles/2309/size-matters

Aylott, M. J., Casella, E., Farrall, K., & Taylor, G. (2010). Estimating the supply of biomass from short-rotation coppice in England, given social, economic and environmental constraints to land availability. *Biofuels*, *1*(5), 719–727. https://doi.org/10.4155/bfs.10.30

Baik, E., Sanchez, D. L., Turner, P. A., Mach, K. J., Field, C. B., & Benson, S. M. (2018). Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(13), 3290–3295. https://doi.org/10.1073/pnas.1720338115

Bateman, I. J., Day, B., Agarwala, M., Bacon, P., Badura, T., Binner, A., … Vinjili, S. (2014). *UK national ecosystem assessment follow-on. Work package report 3: Economic value of ecosystem services*. United Kingdom: UNEP-WCMC, LWEC.

Bateman, I. J., Harwood, A. R., Abson, D. J., Andrews, B., Crowe, A., Dugdale, S., … Termansen, M. (2013). Economic analysis for the UK national ecosystem assessment: Synthesis and scenario valuation of changes in ecosystem services. *Environmental and Resource Economics*, *57*(2), 273–297. https://doi.org/10.1007/s10640-013-9662-y

Bateman, I. J., Harwood, A. R., Mace, G. M., Watson, R. T., Abson, D. J., Andrews, B., … Bird, B. (2013). Bringing ecosystem services into use in the United Kingdom. *Science*, *341*(July), 45–50. https://doi.org/10.1126/science.1234379

BEIS. (2014). Digest of UK Energy Statistics (DUKES): Calorific values. Retrieved from https://www.gov.uk/government/statistics/dukes-calorific-values

BEIS. (2015). Carbon capture and storage knowledge sharing. Retrieved from https://www.gov.uk/government/collections/carbon-capture-and-storage-knowledge-sharing#list-of-peterhead-and-white-rose-key-knowledge-deliverables

BEIS. (2018). *Updated short-term traded carbon values: Used for modelling purposes*. Retrieved from https://www.gov.uk/government/

Bell, S., & McIntosh, E. (2001). *Short rotation coppice in the landscape*. Cambridge, UK: Forestry Commission.

Beringer, T., Lucht, W., & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, *3*(4), 299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x

Berndes, G. (2008). *Water demand for global bioenergy production: Trends, risks and opportunities*. Berlin: WBGU.

Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., & Essery, R. L. H. (2011). The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes. *Geoscientific Model Development*, *4*, 677–699. https://doi.org/10.5194/gmd-4-677-2011

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., … Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. *Energy and Environmental Science*, *11*(5), 1062–1176. https://doi.org/10.1039/c7ee02342a

Bui, M., Fajardy, M., & Dowell, N. M. (2017). Thermodynamic evaluation of carbon negative power generation: Bio-energy CCS (BECCS). *Energy Procedia*, *114*, 6010–6020. https://doi.org/10.1016/j.egypro.2017.03.1736

Byers, E. A., Hall, J. W., & Amezaga, J. M. (2014). Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, *25*, 16–30. https://doi.org/10.1016/j.gloenvcha.2014.01.005

Byers, E. A., Qadrdan, M., Leathard, A., Alderson, D., Hall, J. W., Amezaga, J. M., …Chaudry, M. (2015). Cooling water for Britain's future electricity supply. *Proceedings of the Institution of Civil Engineers - Energy*, *168*(3), 188–204. https://doi.org/10.1680/ener.14.00028

Carrasco, F., Grathwohl, S., Maier, J., Ruppert, J., & Scheffknecht, G. (2019). Experimental investigations of oxyfuel burner for cement production application. *Fuel*, *236*, 608–614. https://doi.org/10.1016/j.fuel.2018.08.135

Cavalett, O., Slettmo, S. N., & Cherubini, F. (2018). Energy and environmental aspects of using eucalyptus from Brazil for energy and transportation services in Europe. *Sustainability*, *10*(11), 1–18. https://doi.org/10.3390/su10114068

Clifton-Brown, J., Hastings, A., Mos, M., McCalmont, J. P., Ashman, C., Awty-Carroll, D., … Scurlock, J. (2017). Progress in upscaling *Miscanthus* biomass production for the European bio-economy with seed-based hybrids. *GCB Biology*, *9*(1), 6–17. https://doi.org/10.1111/gcbb.12357

Committee on Climate Change. (2015). *Sectoral scenarios for the fifth carbon budget*. London, UK. https://www.theccc.org.uk/wp-content/uploads/2015/11/Sectoral-scenarios-for-the-fifth-carbon-budget-Committee-on-Climate-Change.pdf

Committee on Climate Change. (2016). *UK climate change risk assessment 2017*. London, UK. https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Synthesis-Report-Committee-on-Climate-Change.pdf

Committee on Climate Change. (2018a). *Biomass in a low-carbon economy*. Retrieved from https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf

Committee on Climate Change. (2018b). *Reducing UK emissions: 2018 Progress report to parliament*. London, UK.

Cormen, T. H., Leiserson, C. E., Rivest, R. L., & Stein, C. (1990). *Introduction to algorithms*. Cambridge, MA: MIT Press.

Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., … Masera, O. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, *7*(5), 916–944. https://doi.org/10.1111/gcbb.12205

Daggash, H. A., Heuberger, C. F., & Mac Dowell, N. (2019). The role and value of negative emissions technologies in decarbonising the UK energy system. *International Journal of Greenhouse Gas Control*, *81*, 181–198. https://doi.org/10.1016/j.ijggc.2018.12.019

Daioglou, V., Doelman, J. C., Wicke, B., Faaij, A., & van Vuuren, D. P. (2019). Integrated assessment of biomass supply and demand in climate change mitigation scenarios. *Global Environmental Change*, *54*, 88–101. https://doi.org/10.1016/j.gloenvcha.2018.11.012

DEFRA. (2019a). *Crops grown for bioenergy in the UK: 2017*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/775243/nonfood-statsnotice2017-31jan19i.pdf

DEFRA. (2019b). June survey of agriculture and horticulture. Retrieved from https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june

Dockerty, T., Appleton, K., & Lovett, A. (2012). Public opinion on energy crops in the landscape: Considerations for the expansion of renewable energy from biomass. *Journal of Environmental Planning and Management*, *55*(9). https://doi.org/10.1080/09640568.2011.636966

Drax. (2015). *White rose carbon capture and storage (CCS) project*. Retrieved from http://www.whiteroseccs.co.uk/your-questions-answered/operations

Drax. (2018). *How to switch a power station off coal*. Retrieved from https://www.drax.com/technology/switch-power-station-off-coal/

Dubgaard, A., Kallesøe, M. F., Petersen, M. L., & Ladenburg, J. (2002). *Cost-benefit analysis of the skjern river restoration project*. Copenhagen, Denmark: Royal Veterinary and Agricultural University.

Eigenbrod, F., Bell, V. A., Davies, H. N., Heinemeyer, A., Armsworth, P. R., & Gaston, K. J. (2011). The impact of projected increases in urbanization on ecosystem services. *Proceedings of the Royal Society B*, *278*, 3201–3208. https://doi.org/10.1098/rspb.2010.2754

Ekins, P., Hughes, N., Pye, S., Macrory, R., Milligan, B., Haszeldine, S., & Watson, J. (2017). *The role of CCS in meeting climate policy targets*. London, UK: Global Carbon Capture and Storage Institute (GCCSI).

Environment Agency. (2009). *Ecosystem services case studies*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291631/scho0409bpvm-e-e.pdf

Environment Agency. (2013). *Water stressed areas – Final classification*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/244333/water-stressed-classification-2013.pdf

Environment Agency. (2015). *Energy crops and floodplain flows*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/480799/Energy_crops_and_floodplain_flows_report.pdf

Environment Agency. (2018a). *Climate change impacts and adaptation report*. Retrieved from www.enr.gov.nt.ca/_live/documents/content/NWT_climate_change_impacts_and_adaptation_report.pdf

Environment Agency. (2018b). *Estimating the economic costs of the 2015 to 2016 winter floods*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/672087/Estimating_the_economic_costs_of_the_winter_floods_2015_to_2016.pdf

ETI. (2016a). *Delivering greenhouse gas emission savings through UK bioenergy value chains*. Loughborough, UK: Energy Technologies Institute.

ETI. (2016b). *The evidence for deploying bioenergy with CCS (BECCS) in the UK*. Loughborough, UK: Energy Technologies Institute.

European Commission. (2001). *Integrated Pollution Prevention and Control (IPPC) reference document on the application of best available techniques to industrial cooling systems*. Retrieved from http://eippcb.jrc.ec.europa.eu/reference/BREF/cvs_bref_1201.pdf

European Commission. (2016). *Environmental implications of increased reliance of the EU on biomass from the south east US*. Retrieved from http://bookshop.europa.eu/en/environmental-implications-of-increased-reliance-of-the-eu-on-biomass-from-the-south-east-us-pbKH0116687/

FAO, IIASA, ISRIC, ISSCAS, JRC. (2012). *Harmonized world soil database (version 1.2)*. Rome, Italy and Laxenburg, Austria: FAO and IIASA.

Fezzi, C., & Bateman, I. J. (2011). Structural agricultural land use modeling for spatial agro-environmental policy analysis. *American Journal of Agricultural Economics*, *93*(4), 1168–1188. https://doi.org/10.1093/ajae/aar037

Finch, J. W., & Riche, A. B. (2010). Interception losses from Miscanthus at a site in south-east England – An application of the Gash model. *Hydrological Processes*, *24*, 2594–2600. https://doi.org/10.1002/hyp.7673

Finney, K. N., Akram, M., Diego, M. E., Yang, X., & Pourkashanian, M. (2019). Carbon capture technologies. *Bioenergy with Carbon Capture and Storage*. https://doi.org/10.1016/b978-0-12-816229-3.00002-8

Forest Research. (2019). Typical calorific values of fuels. Retrieved from https://www.forestresearch.gov.uk/tools-and-resources/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/

Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., … Mulugetta, Y. (2017). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, *3*, 10–15. https://doi.org/10.1038/s41560-017-0036-5

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., … Yamagata, Y. (2014). Betting on negative emissions. *Nature Climate Change*, *4*(10), 850–853. https://doi.org/10.1038/nclimate2392

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., … Minx, J. C. (2017). Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*, 2–4.

Georgescu, M., Lobell, D. B., & Field, C. B. (2011). Direct climate effects of perennial bioenergy crops in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(11), 4307–4312. https://doi.org/10.1073/pnas.1008779108

Gissi, E., Gaglio, M., & Reho, M. (2016). Sustainable energy potential from biomass through ecosystem services trade-off analysis: The case of the Province of Rovigo (Northern Italy). *Ecosystem Services*, *18*, 1–19. https://doi.org/10.1016/j.ecoser.2016.01.004

Hankin, B., Chappell, N., Page, T., Kipling, K., Whitling, M., & Burgess-Gamble, L. (2018). *Mapping the potential for working with natural processes – Technical report*. Retrieved from https://www.gov.uk/government/organisations/environment-agency/about/research

Harris, Z. M., Alberti, G., Viger, M., Jenkins, J. R., Rowe, R., McNamara, N. P., & Taylor, G. (2017). Land-use change to bioenergy: Grassland to short rotation coppice willow has an improved carbon balance. *GCB Bioenergy*, *9*(2), 469–484. https://doi.org/10.1111/gcbb.12347.

Harris, Z. M., Spake, R., & Taylor, G. (2015). Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*, *82*, 27–39. https://doi.org/10.1016/j.biombioe.2015.05.008

Hastings, A., Clifton-Brown, J., Wattenbach, M., Mitchell, C. P., & Smith, P. (2009). The development of MISCANFOR, a new Miscanthus crop growth model: Towards more robust yield predictions under different climatic and soil conditions. *GCB Bioenergy*, *1*(2), 154–170. https://doi.org/10.1111/j.1757-1707.2009.01007.x

Hastings, A., Mos, M., Yesufu, J. A., Mccalmont, J., Schwarz, K., Shafei, R., … Hill, J. (2017). Economic and environmental assessment of seed and rhizome propagated Miscanthus in the UK. *Frontiers in Plant Science*, *8*(June), 1–16. https://doi.org/10.3389/fpls.2017.01058

Hastings, A., Tallis, M. J., Casella, E., Matthews, R. W., Henshall, P. A., Milner, S., … Taylor, G. (2014). The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. *GCB Bioenergy*, *6*(2), 108–122. https://doi.org/10.1111/gcbb.12103

Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, *8*(2), 151–155. https://doi.org/10.1038/s41558-017-0064-y

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., … Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*, 816–821. https://doi.org/10.1038/nclimate1911

HM Government. (2018). *A green future: Our 25 year plan to improve the environment*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf

HM Treasury. (2018). *The green book: Central government guidance on appraisal and evaluation*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/685903/The_Green_Book.pdf

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., … Zhou, G. (2018). Impacts of 1.5°C global warming on natural and human systems. In V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, … T. Waterfield (Eds.), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. In press. Retrieved from https://www.ipcc.ch/sr15/chapter/chapter-3/

Hof, C., Voskamp, A., Biber, M. F., Böhning-Gaese, K., Engelhardt, E. K., Niamir, A., … Hickler, T. (2018). Bioenergy cropland expansion may offset positive effects of climate change mitigation for global vertebrate diversity. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(52), 13294–13299. https://doi.org/10.1073/pnas.1807745115

Holder, A. J., McCalmont, J. P., McNamara, N. P., Rowe, R., & Donnison, I. S. (2018). Evapotranspiration model comparison and an estimate of field scale Miscanthus canopy precipitation interception. *GCB Bioenergy*, *38*(1), 42–49. https://doi.org/10.1111/gcbb.12503

Holland, R. A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D., & Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, *46*, 30–40. https://doi.org/10.1016/j.rser.2015.02.003

Holland, R. A., Scott, K., Hinton, E. D., Austen, M. C., Barrett, J., Beaumont, N., … Taylor, G. (2016). Bridging the gap between energy and the environment. *Energy Policy*, *92*, 181–189. https://doi.org/10.1016/j.enpol.2016.01.037

Hooper, T., Austen, M. C., Beaumont, N., Heptonstall, P., Holland, R. A., Ketsopoulou, I., … Winskel, M. (2018). Do energy scenarios pay sufficient attention to the environment? Lessons from the UK to support improved policy outcomes. *Energy Policy*, *115*, 397–408. https://doi.org/10.1016/j.enpol.2018.01.028

IPCC. (2012). *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY: Cambridge University Press, 582 pp.

IPCC. (2019). *IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change. Retrieved from https://www.ipcc.ch/srccl/

Jackson, S., Fuller, D., Dunsford, H., Mowbray, R., Hext, S., MacFarlane, R., & Haggett, C. (2008). *Tranquillity mapping: Developing a robust methodology for planning support*. Retrieved from www.cpre.org.uk/resources/countryside/item/download/542

Jenkins, G. J., Murphy, J. M., Sexton, D. S., Lowe, J. A., Jones, P., & Kilsby, C. G. (2009). *UK climate projections: Briefing report*. Retrieved from http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87852&filetype=pdf

Keller, A. A., Fournier, E., & Fox, J. (2015). Minimizing impacts of land use change on ecosystem services using multi-criteria heuristic analysis. *Journal of Environmental Management*, *156*, 23–30. https://doi.org/10.1016/j.jenvman.2015.03.017

Kelly, B. (2006). *Nexant parabolic trough solar power plant systems analysis*. Retrieved from www.nrel.gov/docs/fy06osti/40163.pdf

Koornneef, J., van Breevoort, P., Hamelinck, C., Hendriks, C., Hoogwijk, M., Koop, K., … Camps, A. (2012). Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control*, *11*, 117–132. https://doi.org/10.1016/j.ijggc.2012.07.027

Kumar, A., & Sokhansanj, S. (2007). Switchgrass (*Panicum vigratum* L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. *Bioresource Technology*, *98*(5), 1033–1044. https://doi.org/10.1016/j.biortech.2006.04.027

Le, P. V. V., Kumar, P., & Drewry, D. T. (2011). Implications for the hydrologic cycle under climate change due to the expansion of bioenergy crops in the Midwestern United States. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(37), 15085–15090. https://doi.org/10.1073/pnas.1107177108

Ledoux, L. (2004). Wetland values in the context of flood and coastal defence appraisal. Proceedings of a Workshop, CSERGE Working Paper PA 04-01. Norwich, UK.

Leschine, T. M., Wellman, K. F., & Green, T. H. (1997). *The economic value of wetlands: Wetlands' role in flood protection in western Washington*. Washington, DC: University of Washington.

Lovett, A., Sünnenberg, G., & Dockerty, T. (2014). The availability of land for perennial energy crops in Great Britain. *GCB Bioenergy*, *6*(2), 99–107. https://doi.org/10.1111/gcbb.12147

Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., … Hertwich, E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature Communications*, *10*(1), 1–13. https://doi.org/10.1038/s41467-019-13067-8

Mander, S., Anderson, K., Larkin, A., Gough, C., & Vaughan, N. (2017). The role of bio-energy with carbon capture and storage in meeting the climate mitigation challenge: A whole system perspective. *Energy Procedia*, *114*, 6036–6043. https://doi.org/10.1016/j.egypro.2017.03.1739

McCalmont, J. P., Robson, P., McNamara, N. P., Clifton-Brown, J., Richter, G. M., Hastings, A., & Donnison, I. S. (2015). Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. *GCB Bioenergy*, *9*(3), 489–507. https://doi.org/10.1111/gcbb.12294

McCauley, D. J. (2006). Selling out on nature. *Nature*, *443*(7107), 27–28. https://doi.org/10.1038/443027a

Mendoza-Tinoco, D., Guan, D., Zeng, Z., Xia, Y., & Serrano, A. (2017). Flood footprint of the 2007 floods in the UK: The case of the Yorkshire and The Humber region. *Journal of Cleaner Production*, *168*, 655–667. https://doi.org/10.1016/j.jclepro.2017.09.016

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being synthesis*. Retrieved from http://www.millenniumassessment.org/documents/document.356.aspx.pdf

Milner, S., Holland, R. A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., … Taylor, G. (2016). Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy*, *8*(2), 317–333. https://doi.org/10.1111/gcbb.12263

Mishra, S. K., Negri, M. C., Kozak, J., Cacho, J. F., Quinn, J., Secchi, S., & Ssegane, H. (2019). Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy*, *11*(6), 748–762. https://doi.org/10.1111/gcbb.12602

Muri, H. (2018). The role of large-scale BECCS in the pursuit of the 1.5°C target: An Earth system model perspective. *Environmental Research Letters*, *13*. https://doi.org/10.1088/1748-9326/aab324

Nicolas, C., Chen, Y. H., Morris, J., Winchester, N., & Paltsev, S. (2017). *Bioenergy with carbon capture and storage: Key issues and major challenges*. Presented at the 20th Annual Conference on Global Economic Analysis, West Lafayette, IN, USA.

Niquisse, S., & Cabral, P. (2017). Assessment of changes in ecosystem service monetary values in Mozambique. *Environmental Development*, *25*, 12–22. https://doi.org/10.1016/j.envdev.2017.09.003

Noothout, P., Wiersma, F., Hurtado, O., Macdonald, D., Kemper, J., & Van Alphen, K. (2014). CO_2 pipeline infrastructure – Lessons learnt. *Energy Procedia*, *63*, 2481–2492. https://doi.org/10.1016/j.egypro.2014.11.271

Obersteiner, M., Bednar, J., Wagner, F., Gasser, T., Ciais, P., Forsell, N., … Schmidt-Traub, G. (2018). How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, *8*(1), 7–10. https://doi.org/10.1038/s41558-017-0045-1

Ode, Å., Fry, G., Tveit, M. S., Messager, P., & Miller, D. (2009). Indicators of perceived naturalness as drivers of landscape preference. *Journal of Environmental Management*, *90*(1), 375–383. https://doi.org/10.1016/j.jenvman.2007.10.013

Oliver, R. J., Blyth, E., Taylor, G., & Finch, J. W. (2015). Water use and yield of bioenergy poplar in future climates: Modelling the interactive effects of elevated atmospheric CO_2 and climate on productivity and water use. *GCB Bioenergy*, *7*(5), 958–973. https://doi.org/10.1111/gcbb.12197

Pogson, M., Richards, M., Dondini, M., Jones, E. O., Hastings, A., & Smith, P. (2016). ELUM: A spatial modelling tool to predict soil greenhouse gas changes from land conversion to bioenergy in the UK. *Environmental Modelling and Software*, *84*, 458–466. https://doi.org/10.1016/j.envsoft.2016.07.011

Poyry. (2017). *The future of biomass in the renewables portfolio: A report to drax power*. https://www.drax.com/wp-content/uploads/2017/12/Future-biomass-renewables-portfolio-Poyry-Drax.pdf

Purcell, A. T., & Lamb, R. J. (1998). Preference and naturalness: An ecological approach. *Landscape and Urban Planning*, *42*(1), 57–66. https://doi.org/10.1016/S0169-2046(98)00073-5

Renewable Fuels Agency. (2008). The Gallagher review of the indirect effects of biofuel production. Retrieved from https://www.unido.org/sites/default/files/2009-11/Gallagher_Report_0.pdf

Richards, M., Pogson, M., Dondini, M., Jones, E. O., Hastings, A., Henner, D. N., … Smith, P. (2017). High-resolution spatial modelling of greenhouse gas emissions from land-use change to energy crops in the United Kingdom. *GCB Bioenergy*, *9*(3), 627–644. https://doi.org/10.1111/gcbb.12360

Risk Management Solutions. (2019). *Investing in flood risk management and defences*. Retrieved from https://www.rms.com/sites/default/files/2020-03/Flood-Re-RMS-Results-Summary-ABI-version.a_0_0.pdf

Robertson, G. P., Hamilton, S. K., Barham, B. L., Dale, B. E., Izaurralde, R. C., Jackson, R. D., … Tiedje, J. M. (2017). Cellulosic biofuel contributions to a sustainable energy future: Choices and outcomes. *Science*, *356*. https://doi.org/10.1126/science.aal2324

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., … Vilariño, M. V. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In *IPCC special report global warming of 1.5°C*. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter2_Low_Res.pdf

Rose, S., & Zdenka, R. (2015). Energy crops and floodplain flows. Retrieved fromhttps://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/480799/Energy_crops_and_floodplain_flows_report.pdf

Rowe, R., Whitaker, J., Freer-Smith, P. H., Chapman, J., Ryder, S., Ludley, K. E., … Taylor, G. (2011). Counting the cost of carbon in bioenergy systems: Sources of variation and hidden pitfalls when comparing life cycle assessments. *Biofuels*, *2*(6), 693–707. https://doi.org/10.4155/bfs.11.131

Rubin, E. S., Davison, J. E., & Herzog, H. J. (2015). The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, *40*, 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., & Jenkins, M. (2018). The global status and trends of Payments for Ecosystem Services. *Nature Sustainability*, *1*, 136–144. https://doi.org/10.1038/s41893-018-0033-0

Seddighi, S., Clough, P. T., Anthony, E. J., Hughes, R. W., & Lu, P. (2018). Scale-up challenges and opportunities for carbon capture by oxy-fuel circulating fluidized beds. *Applied Energy*, *232*, 527–542. https://doi.org/10.1016/j.apenergy.2018.09.167

Shukla, P. R., Skea, J., Slade, R., van Diemen, R., Haughey, E., Malley, J., … Pereira, J. P. (2019). Technical summary, 2019. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, … J. Malley, (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In press. Retrieved from https://www.ipcc.ch/srccl/cite-report/

Skärbäck, E., & Becht, P. (2005). Landscape perspective on energy forests. *Biomass and Bioenergy*, *28*, 151–159. https://doi.org/10.1016/j.biombioe.2004.08.008

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. *Nature Climate Change*, *4*, 99–105. https://doi.org/10.1038/nclimate2097

Small, N., Munday, M., & Durance, I. (2017). The challenge of valuing ecosystem services that have no material benefits. *Global Environmental Change*, *44*, 57–67. https://doi.org/10.1016/j.gloenvcha.2017.03.005

Smith, J., Gottschalk, P., Bellarby, J., Chapman, S., Lilly, A., Towers, W., … Smith, P. (2010). Estimating changes in Scottish soil carbon stocks using ECOSSE. I. Model description and uncertainties. *Climate Research*, *45*, 1790192. https://doi.org/10.3354/cr00902

Smith, L. J., & Torn, M. S. (2013). Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, *118*(1), 89–103. https://doi.org/10.1007/s10584-012-0682-3

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., … Keesstra, S. (2019). Impacts of land-based greenhouse gas removal options on ecosystem services and the United Nations Sustainable Development Goals. *Annual Review of Environment and Resources*. https://doi.org/10.1146/annurev-environ-101718-033129

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Yongsung, C. (2016). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

Stephens, W., & Hess, T. (2001). *Review of the effects of energy crops on hydrology*. Bedford, UK: Cranfield University.

Stoy, P. C., Ahmed, S., Jarchow, M., Rashford, B., Swanson, D., Albeke, S., … Poulter, B. (2018). Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales. *BioScience*, *68*(2), 100–111. https://doi.org/10.1093/biosci/bix145

Tallis, M. J., Casella, E., Henshall, P. A., Aylott, M. J., Randle, T. J., Morison, J. I. L., & Taylor, G. (2013). Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. *GCB Bioenergy*, *5*(1), 53–66. https://doi.org/10.1111/j.1757-1707.2012.01191.x

Tarr, N. M., Rubino, M. J., Costanza, J. K., McKerrow, A. J., Collazo, J. A., & Abt, R. C. (2017). Projected gains and losses of wildlife habitat from bioenergy-induced landscape change. *GCB Bioenergy*, *9*(5), 909–923. https://doi.org/10.1111/gcbb.12383

Terravesta. (2013). Terravesta offers new contracts as Miscanthus prices hit an all time high. Retrieved from https://www.terravesta.com/news/terravesta-offers-new-contracts-as-miscanthus-prices-hit-all-time-high/

Turner, P. A., Mach, K. J., Lobell, D. B., Benson, S. M., Baik, E., Sanchez, D. L., & Field, C. B. (2018). The global overlap of bioenergy and carbon sequestration potential. *Climatic Change*, *148*(1-2), 1–10. https://doi.org/10.1007/s10584-018-2189-z

UK Carbon Capture and Storage Cost Reduction Task Force. (2013). *CCS Cost Reduction Task Force Final Report*. London, UK: UK Carbon Capture and Storage Cost Reduction Task Force.

UK National Ecosystem Assessment. (2011). *UK national ecosystem assessment: Synthesis of the key findings*. Cambridge: UNEP-WCMC.

UNFCCC. (2016). *Report of the conference of the parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*. Paris, France: United Nations Framework Convention on Climate Change (UNFCC).

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. Retrieved from https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

United Nations Environment Programme. (2019). *Emissions Gap Report 2019*. Nairobi: UNEP. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/30797/EGR2019.pdf?sequence=1&isAllowed=y

Upham, P., & Shackley, S. (2006). The case of a proposed 21.5 MWe biomass gasifier in Winkleigh, Devon: Implications for governance of renewable energy planning. *Energy Policy*, *34*(15), 2161–2172. https://doi.org/10.1016/j.enpol.2005.04.001

Vanlooke, A., Bernacchi, C. J., & Twine, T. E. (2010). The impacts of Miscanthus×giganteus production on the Midwest US hydrologic cycle. *GCB Bioenergy*, *2*, 180–191. https://doi.org/10.1111/j.1757-1707.2010.01053.x

Vaughan, N. E., Gough, C., Mander, S., Littleton, E. W., Welfle, A., Gernaat, D. E. H. J., & van Vuuren, D. P. (2018). Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environmental Research Letters*, *13*. https://doi.org/10.1088/1748-9326/aaaa02

Whittaker, C., Mortimer, N., Murphy, R., Hillier, J., & Smith, P. (2009). *The life cycle analysis of using biomass for heat and electricity production in the UK*. https://doi.org/10.13140/RG.2.1.3580.7761

Whitaker, J., Field, J. L., Bernacchi, C. J., Cerri, C. E. P., Ceulemans, R., Davies, C. A., … McNamara, N. P. (2018). Consensus, uncertainties and challenges for perennial bioenergy crops and land use. *GCB Bioenergy*, *10*(3), 150–164. https://doi.org/10.1111/gcbb.12488

Wynn, S., Alves, L., & Carter, R. (2016). *Refining estimates land for biomass*. Helsby, UK: ADAS.

Zhai, H., Rubin, E. S., & Versteeg, P. L. (2011). Water use at pulverized coal power plants with postcombustion carbon capture and storage. *Environmental Science & Technology*, *45*, 2479–2485. https://doi.org/10.1021/es1034443

Zhang, D., Bui, M., Fajardy, M., Patrizio, P., Kraxner, F., & Dowell, N. M. (2019). Unlocking the potential of BECCS with indigenous sources of biomass at a national scale. *Sustainable Energy and Fuels*, *4*(1), 226–253. https://doi.org/10.1039/c9se00609e

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Donnison C, Holland RA, Hastings A, Armstrong L-M, Eigenbrod F, Taylor G. Bioenergy with Carbon Capture and Storage (BECCS): Finding the win–wins for energy, negative emissions and ecosystem services—size matters. *GCB Bioenergy*. 2020;00:1–19. https://doi.org/10.1111/gcbb.12695