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REVIEW

Upscaling miscanthus production in the United Kingdom: The benefits, challenges, and trade-offs

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Abstract

The UK sixth carbon budget has recommended domestic biomass supply should increase to meet growing demand, planting a minimum of 30,000 hectares of perennial energy crops a year by 2035, with a view to establishing 700,000 hectares by 2050 to meet the requirements of the balanced net zero pathway. Miscanthus is a key biomass crop to scale up domestic biomass production in the United Kingdom. A cohesive land management strategy, based on robust evidence, will be required to ensure upscaling of miscanthus cultivation maximizes the environmental and economic benefits and minimizes undesirable consequences. This review examines research into available land areas, environmental impacts, barriers to uptake, and the challenges, benefits, and trade-offs required to upscale miscanthus production on arable land and grassland in the United Kingdom. Expansion of perennial biomass crops has been considered best restricted to marginal land, less suited to food production. The review identifies a trade-off between avoiding competition with food production and a risk of encroaching on areas containing high-biodiversity or high-carbon stocks, such as semi-natural grasslands. If areas of land suitable for food production are needed to produce the biomass required for emission reduction, the review indicates there are multiple strategies for miscanthus to complement long-term food security rather than compete with it. On arable land, a miscanthus rotation with a cycle length of 10–20 years can be employed as fallow period for fields experiencing yield decline, soil fatigue, or persistent weed problems. On improved grassland areas, miscanthus presents an option for diversification, flood mitigation, and water quality improvement.

Strategies need to be developed to integrate miscanthus into farming systems in a way that is profitable, sensitive to local demand, climate, and geography, and complements rather than competes with food production by increasing overall farm profitability and resilience.

KEYWORDS

agricultural land classification (ALC), BECCS, biodiversity, bioenergy, biomass, buffer strip, ecosystem services, energy crops, land use, soil carbon (SOC)

1 | INTRODUCTION

Miscanthus is considered a key industrial crop for scaling up domestic production of biomass in the United Kingdom to meet net zero targets (DESNZ, 2023a). Miscanthus is a rhizomatous perennial C4 grass genus originating from SE Asia that is well adapted to the cooler temperate climates of Northwestern Europe (Clifton-Brown et al., 2001; Kalinina et al., 2017; Lewandowski et al., 2000). Once established (2–3 years), the above-ground biomass can be harvested annually for up to 20 years and produce yields of 10–15 $\text{Mg ha}^{-1}\text{year}^{-1}$ on a range of soils under UK climatic conditions (Caslin et al., 2011; DEFRA, 2021; Hastings et al., 2014; Shepherd, Clifton-Brown, et al., 2020). Miscanthus biomass has been principally used in the energy sector as a combustion fuel for heat and electricity generation (DESNZ, 2023b). Miscanthus also has potential to produce liquid and gaseous fuels via gasification, anaerobic digestion, and fermentation (Brosse et al., 2012; Cerazy-Waliszewska et al., 2019; Turner et al., 2021). There are also wide range of applications for miscanthus biomass in the chemical, composite, and construction sectors; it is also sold commercially as animal bedding material (Moll et al., 2020; Yesufu et al., 2020).

1.1 | Why is there a need to upscale biomass production?

The UK Government's Climate Change Act has committed the UK to reducing its greenhouse gas (GHG) emissions to net zero by 2050 (Climate Change Act, 2019). To meet this target, the UK biomass strategy 2023 is promoting the use of biomass from perennial crops, such as miscanthus, as feedstocks for power, heat, and transport, with bioenergy generation to be increasingly coupled with carbon capture and storage (BECCS) as a strategy for GHG removal by providing net-negative carbon emissions (DESNZ, 2023a). The UK renewable energy association, a body representing the bioenergy industry in the United Kingdom, sees a greater role for biomass in decarbonizing heating via further development of combined heat and power (CHP) plants and domestic heat networks (Brown, 2019). Carbon capture, usage, and storage (CCUS) is considered a key technology in the UK government's clean growth industrial strategy and has committed up to £20 billion to establish the UK CCUS sector (BEIS, 2017; DESNZ, 2023c). CCUS facilities are expected to be deployed at scale via six CCUS clusters located in the north of England, Scotland, Merseyside, and South Wales, four of which are expected to be operational by 2030 (BEIS, 2018; DESNZ, 2023c).

Regarding current use of biomass in UK power stations and CHP facilities, over 14 million tonnes of solid biomass was burned in 2021–2022, generating 27 TWh of electricity (DESNZ, 2023b). More than 80% was derived from solid biomass (forest residues, wood residues, and waste wood), mainly in the form of wood pellets or wood chip, around half of which was imported (OFGEM, 2023a). Miscanthus biomass is supplied as bales to straw-fired power stations in Eccleshall (Staffordshire, UK) Ely (Cambridgeshire, UK), Snetterton (Norfolk, UK), and Brigg Biomass Power Plant (North Lincolnshire, UK; Figure 1). In 2021, a total of 44.7 thousand tonnes of miscanthus were burned in these facilities (OFGEM, 2023b). Long-term supply contracts have been arranged between power stations and broker companies who assist with establishment and link production with end users within an ~50 mile radius (Von Hellfeld et al., 2022). Pelletized miscanthus has been supplied commercially at scale to the energy sector, but its use has declined over the last 10 years (OFGEM, 2018). Pelletization, though requiring more energy input during processing, could open more market opportunities for pellet burning systems, commercial and domestic, and has been shown to present a cost- and carbon-effective option compared with pelleted wood (Fusi et al., 2021; Hastings et al., 2017).

The UK government's Climate Change Committee (CCC) has recommended taking measures to reduce reliance on imported biomass by increasing domestic production (CCC, 2018a). Perennial biomass crops, such as miscanthus, have been referred to as a “low-regrets” option for increasing domestic biomass production, owing to their comparatively high yields, low input requirements, and their potential to improve soil quality, biodiversity,

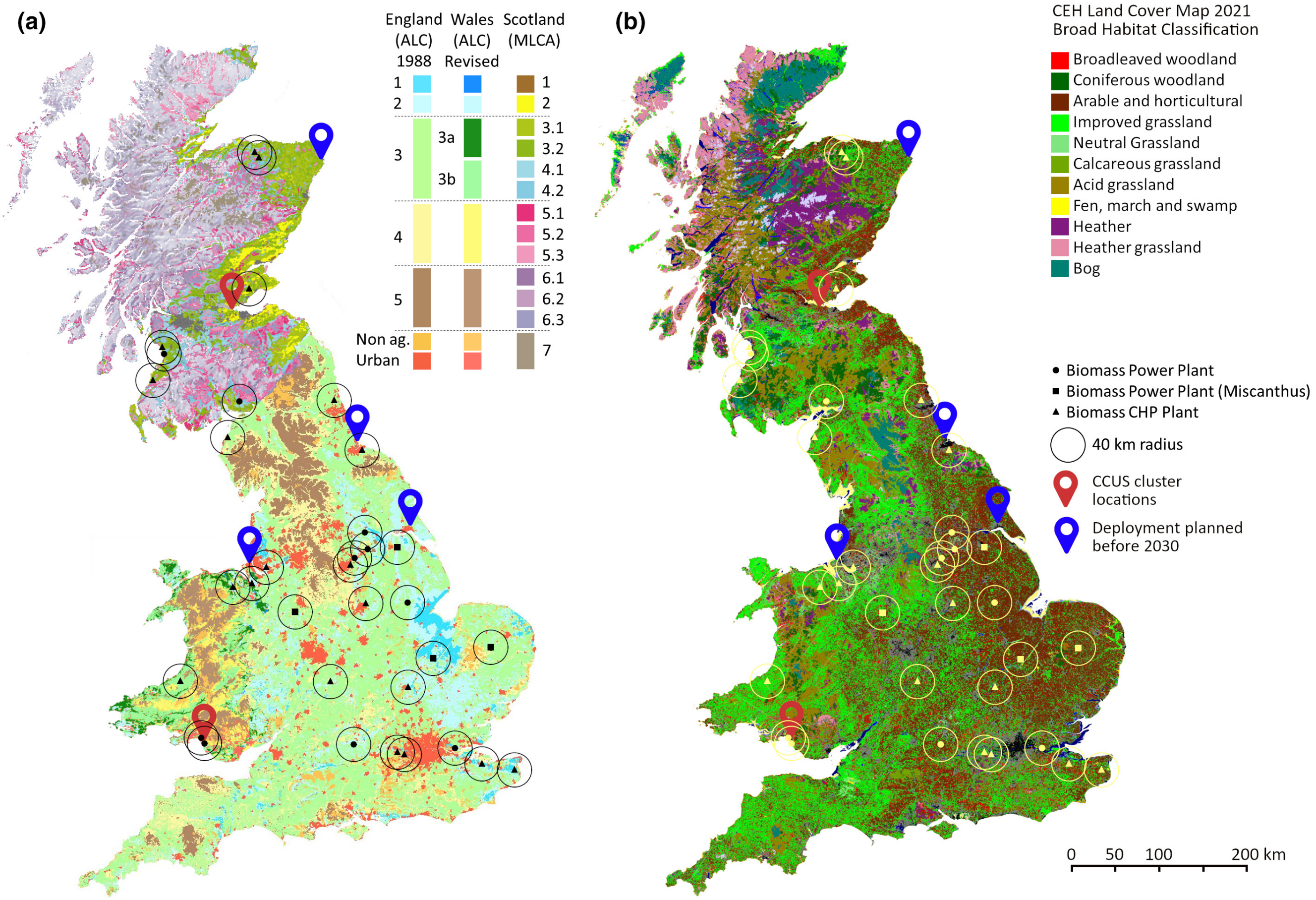

FIGURE 1 Comparison of land areas of Great Britain (GB) by agricultural land classification and broad habitat description including location of existing biomass energy facilities, the biomass used, indicative 40 km biomass catchment radii, and proposed locations of hubs for carbon capture, storage and utilization (CCUS). Map (a) compares bioenergy locations against GB land area by agricultural land classification; England & Wales (ALC; Natural England, 2010; Welsh Government, 2019) and Scotland (MLCA; Soil Survey of Scotland Staff, 1981). Map (b) compares bioenergy locations against estimated land areas by broad habitat classifications (Jackson, 2000) based on the CEH UK Land Cover Map 2021 (LCM2021; Marston et al., 2023); only major habitat categories are included in legend (b). Both maps, (a) and (b), show approximate locations of biomass energy facilities as published in the OFGEM sustainability dataset as >1 MW in capacity and burning either miscanthus, cereal straw, waste-wood or wood/forest residues (OFGEM, 2023). Location markers include bioenergy generator type (power or CHP), generators already using miscanthus, and an approximate 40 km biomass catchment radius, indicative of economic transportation range (Albanito et al., 2019). Locations of planned CCUS hubs (BEIS, 2018) and their priority for deployment (DESNZ, 2023c) are also included.

and capacity for phytoremediation of polluted or degraded land (CCC, 2018a). Numerous lifecycle analyses (LCA) and models have shown that perennial biomass crops have greater potential for reducing GHG emissions than existing annual crops grown for biofuel production, chiefly due to their higher yield per hectare under low-input regimes, reduced land requirement, reduced soil disturbance, and longer life-span of established stands compared to first-generation bioenergy crops (Pogson et al., 2016; Richards et al., 2017; Robson et al., 2020; Rowe et al., 2009; Sims et al., 2006). Co-generation of electricity and heat using UK grown miscanthus in a medium-scale BECCS system (20 MW power, 70 MW heat) has been identified as providing the largest potential GHG reduction benefit per unit of energy, compared with sawmill residue pellets and willow SRC chip (García-Freites et al., 2021).

The UK sixth carbon budget estimates that between 0.23 and 1.4 million hectares of UK land could be used to grow a mixture of dedicated biomass crops by 2050, depending on levels of innovation and public engagement (CCC, 2020). The balanced net zero pathway of the United Kingdom's sixth carbon budget stated a target of planting a minimum of 30,000 hectares of perennial biomass crops a year by 2035, with a view to establishing at least 700,000 hectares by 2050. This could potentially sequester 2–6 $MtCO_2e$ between 2035 and 2050 and an additional 3–10 $MtCO_2e$ if combusted with carbon capture and storage (CCS) (CCC, 2020).

It is recognized that inclusion of biomass crops in a low-carbon future will only be possible if their cultivation and trade can be managed as part of a sustainable land use system, where carbon stocks in soils are maintained or enhanced over time, competition with food and forest production is minimized, and negative impacts of indirect land-use changes are avoided (CCC, 2018a; The Royal Society, 2023). This forms part of a wider debate regarding where the benefits, challenges, and trade-offs are in terms of GHG reduction, biodiversity, and "spare or share" land use strategies (Dauber & Miyake, 2016). The ecosystem service effects of transitioning agricultural land to biomass crop production are dependent on the previous land uses, the location of the crop in the landscape, the scale of planting, the biomass crop selected, and the management regimes applied (McCalmont & Hastings, 2017; Milner et al., 2016; Rowe et al., 2009). While the impacts of land-use change are increasingly well understood, some uncertainties still exist regarding the wider environmental benefits and risks associated with scaling up miscanthus cultivation and how they can best be enhanced or mitigated through land management practices (McCalmont & Hastings, 2017; Wagner & Lewandowski, 2017; Whitaker et al., 2018). This review will examine the current evidence to address the following questions in a UK context:

- How could upscaling miscanthus production be achieved?
- Where could miscanthus production be upscaled?
- What are the main ecosystem service impacts that need to be considered prior to scaling up?
- What are the barriers and incentives for scaling up production from a farmer's perspective?
- What are the main benefits, challenges, and trade-offs of upscaling UK miscanthus production on arable and grassland areas?

2 | WHAT IS THE POTENTIAL FOR UPSCALING MISCANTHUS PRODUCTION IN THE UNITED KINGDOM?

2.1 | How could miscanthus upscaling be achieved?

The majority of current commercially planted stock in the United Kingdom and Europe is the sterile triploid hybrid *Miscanthus x giganteus* (Greef & Deuter, 1993) of which there are a number of variants. In recent years, there has been a number of innovations related to miscanthus breeding and establishment. Considerable progress has been made in breeding novel seeded and clonal hybrids (Clifton-Brown et al., 2017; Clifton-Brown, Harfouche, et al., 2019; Clifton-Brown, Schwarz, et al., 2019). Seven new varieties have been registered for intellectual property protection under the European system for plant breeders (CPVO). These hybrids are being simultaneously tested in multi-location, long-term field trials both within the United Kingdom and across Europe to help match hybrids to specific site requirements and improve crop resilience by reducing reliance on a small number of clones (e.g., *M. x giganteus*). Inter- and intraspecies hybrids of *M. sinensis*, *M. floridulus*, and *M. sacchariflorus* (including the Chinese subspecies *lutarioriparius*) have displayed a range of exceptional yield traits and some display greater tolerance to cold or drought than *M. x giganteus. M. lutarioriparius*, which occurs naturally in riparian areas, has also shown higher photosynthetic and water use efficiency traits than *M. x giganteus* (Feng et al., 2022; Scordia et al., 2020; Yan et al., 2016; Zhao et al., 2021). Results from European field trials on marginal lands have identified a number of seed-based *M. sinensis x sinensis* and *M. sacchariflorus x saccariflorus* hybrids which outperform *M. x giganteus* at least in the first 4 years under UK conditions and across Europe (Awty-Carroll et al., 2023; Nunn et al., 2017; Shepherd et al., 2023). Intra- and interspecies hybrids with a wide range of morphologies continue to be tested for yield stability, nutrient offtakes, and their potential to contribute to soil organic carbon (SOC) from the below-ground turnover of roots and rhizomes, and the contribution from above-ground biomass residues (Magenau et al., 2022). Species have also been observed as having higher soil carbon retention traits either by greater below-ground biomass partitioning (*M. sinensis*) or via improved leaf litter characteristics (*M. lutarioriparius*; Briones et al., 2023).

Cost and supply of rhizomes has been a noted barrier to upscaling production (Hastings et al., 2017). Seed-propagated hybrids, multiplied from seed to a planting plug, have been a major innovation in the industry, allowing much faster multiplication rate than conventional rhizome planting (Clifton-Brown, Harfouche, et al., 2019). Multiplication rates of rhizomes are usually 1:20, seed-based hybrids can achieve multiplication rates of 1:2000 with some *M. sinensis* rates reported up to 1:5000–10,000 (Clifton-Brown, Schwarz, et al., 2019). Encapsulation systems to enhance establishment of vegetatively propagated miscanthus, similar to those used in sugarcane, are currently under development (New Energy Farms, 2022). If successful in the marketplace, these innovations have significant potential to increase upscaling and potentially reduce the cost of establishment by 20%–40%, compared with conventional rhizome propagation (Hastings et al., 2017). Advances have also been made to improve establishment success and growth rate to mature yields. Use of biodegradable mulch films has been shown to better protect seedlings and stimulate early growth (Ashman et al., 2018; Ashman, Awty-Carroll, et al., 2023; Ashman, Wilson, et al., 2023). As a result of these innovations, there is a clear industrial readiness to support upscaling UK production.

2.2 | Where could miscanthus production be upscaled?

In 2020, approximately 121 thousand hectares of UK agricultural land was used for bioenergy crop production, representing around 2.1% of UK arable land (DEFRA, 2021). Of that 121 kha, the majority were high-input annual crops: 75 kha was maize for anaerobic digestion (AD); 29 kha of wheat and 7 kha of sugar beet for ethanol production (DEFRA, 2021). Oilseed rape is not used to produce biodiesel in the United Kingdom, but approximately 27 kha of oilseed rape is exported, a proportion of which is used for biodiesel production in the EU (DEFRA, 2023b; FAO, 2024). Only 10 kha of UK land was used for low-input, perennial biomass crops, comprising 2 kha of short rotation coppice (SRC) and 8 kha of miscanthus (DEFRA, 2021).

The total area of land technically suitable for growing perennial biomass crops across Great Britain, not including any constraints related to maintaining current levels of food production, was estimated as 8.5 M ha (Lovett et al., 2014). This estimate was reached by GIS analysis of the total GB land area excluding roads, rivers, and urban areas; protected zones; existing protected woodlands; areas with a slope >15%; high organic carbon soils (TOC > 30%); and areas with a high "naturalness score" such as National parks and areas of outstanding natural beauty (AONB), commonly referred to as the UKERC 9 constraint mask. Based on this 8.5 M ha area, miscanthus (*M. x giganteus*) was predicted to yield between 7.37 and 13.1 Mg ha^{-1} year^{-1} and perform better in the warmer and wetter climates of the westerly regions of England and Wales (Table 1; Hastings et al., 2014). This area, however, included agricultural land areas used for food production. To avoid issues surrounding 'food versus fuel', cultivation of miscanthus on abandoned or marginal land, not useful for food production, has been proposed (Don et al., 2012; Valentine et al., 2012). However, there is considerable debate regarding how land marginality is classified (Arshad et al., 2021); whether on the basis of physical or socioeconomic characteristics, or a mixture of both (Csikós & Tóth, 2023; Delafield et al., 2023; Donnison et al., 2020; Muscat et al., 2022).

2.2.1 | Land availability based on physical marginality

Agricultural land classifications (ALC) have been used in spatial modelling studies as a way to assess areas of land suitable for biomass crops and the implications of establishing them on those sites (Albanito et al., 2019; Hastings et al., 2014; Lovett et al., 2009, 2014; Milner et al., 2016). The ALC of England and Wales and the Macaulay Land Capability for Agriculture (MLCA) system of Scotland are the main survey methodologies that have been used to grade UK land and provide data to inform decisions within regional planning systems (Bibby et al., 1991; MAFF, 1988). Criteria for grading land vary between approaches, but land is graded according to factors associated with site (slope, micro-relief, and flood risk), soil quality (texture, structure, depth, stoniness, and chemical properties), climate (temperature, rainfall, aspect, exposure, and frost risk), and interacting factors (droughtiness, soil wetness, and erosion risk; Bibby et al., 1991; MAFF, 1988). Site locations are graded on all criteria and the final attributed grade reflects the lowest grade identified from all survey parameters. An overview comparison between the two land grading systems is shown in Table 2. Due to the larger proportion of UK land area being graded under the ALC method, hereafter grades will be referred to by ALC classification only, to aid comparison across UK nations. A summary of the major ALC criteria determining grade and their implications for miscanthus production have been summarized in Table 3.

National planning policies are aimed at protecting the "best and most versatile" (BMV) agricultural land (ALC 1-3a) from degradation or other forms of non-agricultural or urban development. Land graded ALC 3b-5 is considered moderate to very poor, 3b areas may produce a narrow range of food crops. Grades 4–5 are considered physically marginal due to the land presenting moderate to severe limitations to agricultural production that predominantly restricts their use to grassland with occasional low-yielding arable crops, permanent pasture, or rough grazing (Table 2). The post-1988 revised ALC system separates Grade 3 into 3a and 3b, Wales has been mapped to reflect this division, the majority of England has not yet been regraded (Natural England, 2010; Welsh Government, 2019). Of the 8.5 M ha area of land identified by Lovett et al. (2014) as suitable for biomass crops, 21% was on ALC grades 1–2, 59% was on ALC grade 3, and 20% was on ALC grade 4–5 land. When ALC grades 1–3a were excluded, the potential land area reduced to 3.5 M ha, when only ALC grades 4–5 were included, the potential area reduced to 1.4 M ha, a land area equating to the upper planting limit suggested in the sixth carbon budget (CCC, 2020).

TABLE 1 Estimated suitable land area and predicted yield of four perennial biomass crop options presented by NUTS1 regions including mean annual rainfall, potential evapotranspiration, and drought risk.

	Land area potentially suitable[a]	Miscanthus	SRC willow	SRC poplar	SRF poplar			
NUTS 1 region	M ha	Mean harvest yield, dry weight biomass (Mg ha^{-1} year^{-1})				Mean annual rainfall[b] (mm)	Mean annual PET[b] (mm)	No. reported agricultural drought impacts[b] 1975–2012
Scotland	1.079	8.25	8.25	12.94	9.07	1547	422	42
Yorkshire & Humber	0.507	9.39	10.51	13.50	8.97	871	498	40
NW	0.301	11.37	12.1	15.79	10.41	1254	482	18
NE	0.758	8.96	8.28	11.58	10.06	875	479	19
Wales	0.541	12.47	9.81	13.75	9.94	1444	495	13
E Midlands	1.068	7.66	6.90	9.88	10.52	706	516	109
W Midlands	0.777	9.09	7.49	10.05	11.45	765	509	46
E England	0.831	7.37	6.07	8.21	11.62	634	529	276
SW	1.128	13.1	8.34	11.61	10.61	1042	519	138
SE	1.463	9.41	7.55	9.78	11.51	787	511	136
Total/mean	8.453	9.53	8.07	10.17	10.55			

Abbreviation: SRC, short rotation coppice; SRF, short rotation forestry.

[a] Biomass yield and land area estimated as suitable following constraint number of physical, economic, social, and sustainability factors, adapted from Hastings et al. (2014).

[b] Mean annual rainfall, PET, and number of reported agricultural drought impacts by region as reported by (Parsons et al., 2019).

TABLE 2 GB land classifications: Comparing the post-1988 Agricultural land classification system (ALC) of England and Wales (MAFF, 1988), and the Macaulay Land Capability for Agriculture (MLCA) system of Scotland (Bibby et al., 1991).

Predominant farming system[a]	ALC grade and description (England and Wales)	MLCA class and description (Scotland)	Proportion of land potentially suitable for energy crops (%)[b]
Arable & grass ley in rotation	Grade 1—Excellent quality agricultural land: Land with no or very minor limitations to agricultural use. A very wide range of agricultural and horticultural crops can be grown. Yields are high and consistent	Class 1—Land capable of producing a very wide range of crops	21%
	Grade 2—Very good quality agricultural land: Land with minor limitations which affect crop yield, cultivations, or harvesting. A wide range of agricultural and horticultural crops can usually be grown. Some difficulties growing more demanding crops such as winter harvested vegetables and arable root crops. Yields are high but lower or more variable than Grade 1	Class 2—Land capable of producing a wide range of crops	
Mixed	Grade 3a—Good quality agricultural land: Land capable of consistently producing moderate to high yields of a narrow range of arable crops, especially cereals, or moderate yields of a wide range of crops including cereals, grass, oilseed rape, potatoes, sugar beet, and the less demanding horticultural crops	Class 3.1—Consistently high yields of a narrow range of crops and/ or moderate yields of a wider range. Short grass leys are common Class 3.2—Average production though high yields of barley, oats and grass can be obtained. Grass leys are common	59%
	Grade 3b—Moderate quality agricultural land: Land capable of producing moderate yields of a narrow range of crops, principally cereals and grass or lower yields of a wider range of crops or high yields of grass which can be grazed or harvested over most of the year	Class 4.1—A narrow range of crops, primarily grassland with short arable breaks of forage crops and cereals Class 4.2—A narrow range of crops, primarily on grassland with short arable breaks of forage crops	
Improved pasture	Grade 4—Poor quality agricultural land: Land with severe limitations which significantly restrict the range of crops and/or level of yields. It is mainly suited to grass with occasional arable crops (e.g., cereals and forage crops) the yields of which are variable. In moist climates, yields of grass may be moderate to high but there may be difficulties in utilization. The grade also includes very droughty arable land	Class 5.1—Mainly improved grassland. Few problems with pasture establishment and maintenance and potential high yields Class 5.2—Few problems with establishment, may be difficult to maintain Class 5.3—Pasture deteriorates quickly	20%
Rough grazing	Grade 5—Very poor-quality agricultural land—Land with very severe limitations which restrict use to permanent pasture or rough grazing, except for occasional pioneer forage crops	Class 6.1—Rough grazing with a high proportion of palatable plants Class 6.2—Rough grazing with moderate quality plants Class 6.3—Rough grazing with low quality plants	

[a] Predominant land use is a generalization and is indicative of predominant land use, other agricultural land uses may be practiced on ALC graded land.

[b] Based on the 8.5 M ha land area identified as potentially suitable for energy crops, excluding constraints on food production, as identified by Lovett et al. (2014).

The 1.4 M ha estimated to be potentially available on ALC grade 4–5 equates to approximately 8% of the total GB agricultural land area (18 M ha; Lovett et al., 2014). Spatial modelling studies suggest that, once socioeconomic and ecosystem service factors are considered, restricting biomass production to physically marginal land areas

(ALC 4–5) may actually prove either infeasible to meet supply targets or result in worse outcomes in terms of GHG reduction and ecosystem services, a shift toward smaller areas of more productive land might provide a greater number of benefits (Albanito et al., 2019; Delafield et al., 2023; Milner et al., 2016). Clifton-Brown et al. (2023) make the comparison that under the EU Common Agricultural Policy in 1990s, 10% of agricultural land, irrespective of land grade, was required to be "set-aside" as fallow to avoid overproduction. The policy failed to reduce food production, which suggests a 10% conversion of land to perennial biomass crops, irrespective of grade, could theoretically be possible without significant reduction in essential food production (Clifton-Brown et al., 2023). It should also be highlighted that a substantial proportion of arable land is already used for non-food crops or the production of animal feed. For example, maize is grown extensively for use in anaerobic digestion (75 kha) and a proportion of wheat is used for bioethanol production (29 kha) which already directly competes with land available for essential food production (DEFRA, 2021). These crops have far worse environmental credentials and offer little or no long-term benefits to ecosystem services (De Vries et al., 2010; Tudge et al., 2021).

2.2.2 | Land availability based on spatial distribution of end markets

The spatial distribution of end markets is more likely to influence the areas in which miscanthus is established and the potential impacts of upscaling production. Albanito et al. (2019) examined land availability and biomass crop productivity in relation to the spatial distribution of end markets of existing UK power and CHP facilities, using two spatially explicit supply scenarios based on centralized or decentralized provision of BECCS, examining suitable land within a 40-km catchment radius of the generating facilities. Under a mixed biomass crop scenario, to meet a theoretical BECCS mitigation target of 50 $MtCO_2$ per year by 2050, it was estimated 1 M ha of agricultural land would be required and a decentralized system would permit higher GHG mitigation potential than a centralized one, due to a greater total combined area of suitable land via a greater number of land catchments (Albanito et al., 2019). Donnison et al. (2020) also concluded that a decentralized BECCS scenario was more likely to achieve benefits in terms of energy, negative emissions, and ecosystem services. The Albanito et al.'s (2019) study estimated that use of ALC grade 4–5 land would achieve only 36%–46% of the required area to meet their theoretical mitigation target and estimated that either an additional 0.59–0.49 M ha of grade 3 land would be required, or an additional 8 M Mg per year of solid biomass would need to be imported to meet the target. If ALC grade 3 land was also included, potential biomass contributions within the respective catchments increased to meet an additional 5.6% of the energy demand under a centralized scenario, but up to 49% of demand in the decentralized scenario due to access to a greater area of higher yielding land.

A study by Delafield et al. (2023) concluded that restriction of planting to grade 4–5 land would be technically and economically infeasible, beyond an 18-TWh power generation threshold, and suggested the approach of using environmental and food production exclusion zones may limit the positive environmental and economic impacts that could be achieved from biomass crops. The rationale was that the reduced biomass yields achieved on marginal land would require a larger area of land to achieve the same biomass production, which would come with higher costs and fewer potential benefits in terms of ecosystem services than planting on grade 1–3 land (Delafield et al., 2023).

The complete conversion of existing centralized or decentralized CHP generators to biomass suggested in these studies would be infeasible, as would the conversion of all agricultural land within the respective ALC grades. However, these studies bring into focus a decision-making trade-off between food, energy, and carbon sequestration: If more ALC grade 3 land is converted to produce biomass crops, there is an increased likelihood of displacing other forms of food production, increasing the risk of land use change impacts within the United Kingdom or via offshoring. Alternatively, greater use of domestic forest resources or larger scale importation of biomass would be required, both of which lead to different sets of LUC impacts (Calvin et al., 2021; CCC, 2018a; Konadu et al., 2015).

2.2.3 | Land availability based on agricultural systems

Spatial studies suggest there is sufficient land available to support upscaling production, although to meet the more ambitious planting targets, it is likely a proportion of ALC grade 3 land would be required. As stated previously, marginal ALC 4–5 grade land does comprise 1.4 M ha, but this land is mainly in upland areas, and predominantly used for extensive livestock production (MAFF, 1988; Figure 1). Land use in these areas has developed because of the limitations to other forms of agricultural production, these limitations may also reduce the potential for planting and harvesting miscanthus in these areas, reduce potential yields and therefore the amount of carbon sequestered (Table 3).

TABLE 3 Agricultural Land Classifications (ALC) of England and Wales, examples of key criteria and grade implications for growing miscanthus. Adapted from ALC revised guidelines (MAFF, 1988).

<table>
<tr><th>Grade criterion</th><th>Implications for Miscanthus</th></tr>
<tr><td colspan="2">Climate criteria</td></tr>
<tr><td>Limitations increase as average annual rainfall increases and average temperature decreases. Therefore, the areas currently graded poorest under ALC are wetter and colder. However, drought risk has become a more limiting factor, especially in the east of England. It has been recommended the ALC method is updated to reflect latest data and meteorological modeling, to better account for factors of soil droughtiness and wetness (Rollett & Williams, 2021, 2022)</td><td>Temperature, annual rainfall, and soil water retention have the strongest influence on miscanthus yields. Miscanthus does not grow <6°C but may survive −14°C (Caslin et al., 2011). Growing season shortened by persistent cold winter temperatures and late spring frosts. The growing season is also shortened by early senescence triggered by periods of drought (Nunn et al., 2017). Summer droughts may cause yield reductions, genotypes need to be matched to site climatic conditions</td></tr>
<tr><td colspan="2">Site criteria</td></tr>
<tr><td>Gradient—effects mechanized operations:
Grade 1–3a have a slope limit of <7°;
3b, 11°; Grade 4, 18°; Grade 5 > 18°.
Microrelief—Complex changes of slope angle and direction over short distances and the presence of rocky outcrops and obstruction</td><td>Due to requirements of mechanized harvesting, a slope limit of 8.5° (<15%) was recommended (Lovett et al., 2014). Limiting miscanthus to grade 3 or above for gradient. Miscanthus will require a level site with few obstructions to mechanical harvesting</td></tr>
<tr><td>Grade according to flood risk in summer.[a]
<table>
<tr><td>Grade 3a</td><td>≤2 days, in 3–9 years
2–4 days, in 10–15 years</td></tr>
<tr><td>Grade 3b</td><td>2–4 days, in 3–9 years
>4 days, in 10–14 years</td></tr>
<tr><td>Grade 4</td><td>1–4 days, in ≤3 years
>4 days, in 3–9 years</td></tr>
<tr><td>Grade 5</td><td>>4 days, in ≤3 years</td></tr>
</table></td><td>Miscanthus could be planted on all grades for flood risk. It been shown to be effective at intercepting precipitation, improving soil water infiltration, and providing resistance to overland flows, making it useful as a flood defense measure (Holder, Rowe, et al., 2019; Shepherd, Clifton-Brown, et al., 2020). It has been shown to survive flooding with little impact on yield (De Vega et al., 2021; Kam et al., 2020). Heavy clay soils prone to waterlogging over winter/early spring may limit accessibility for harvesting machinery and increase soil compaction (Caslin et al., 2011)</td></tr>
<tr><td colspan="2">Soil criteria</td></tr>
<tr><td>The soil grading method is complicated and not possible to fully summarize here. It involves assessment of soil texture, structure, depth, stoniness, and chemical fertility. Texture and structure are most important for water movement, retention, and aeration. Structure improves with length of time it is undisturbed. Clay soils reduce permeability, silt/sandy soils are weak structured and prone to erosion and drought. Soils with sand top soils are graded within 3b-5. Interactive limitations are associated with soil wetness, droughtiness and erosion risk. Any sites with soil toxicity will be graded: arable, not suitable for human consumption <3b, pastureland <4, rough grazing, 5 or unusable</td><td>Miscanthus has been shown to produce reasonable yields on a range of soils, with optimum pH of between 5.5 and 7.5 (Caslin et al., 2011). Miscanthus performs well on clay soils, moderately well on heavy clay and less well on sandy soils, depending on water holding capacity and rainfall (Reinhardt et al., 2021). High yield losses due to persistent droughts have been reported. Higher SOC gains may be achieved in clay soils (Bai & Cotrufo, 2022). Miscanthus has been shown to be tolerant of a wide range of trace elements and effective option for phytoremediation of contaminated soils (Moreira et al., 2021; Nsanganwimana et al., 2014)</td></tr>
<tr><td>
<table>
<tr><th rowspan="2">Grade</th><th rowspan="2">Soil depth (cm)</th><th colspan="2">Stoniness*</th></tr>
<tr><th>Stones >2 cm</th><th>Stones >6 cm</th></tr>
<tr><td>Grade 3a</td><td>≥30</td><td>15</td><td>10</td></tr>
<tr><td>Grade 3b</td><td>≥20</td><td>35</td><td>20</td></tr>
<tr><td>Grade 4</td><td>≥15</td><td>50</td><td>35</td></tr>
<tr><td>Grade 5</td><td><15</td><td>>50</td><td>>35</td></tr>
</table>
*% hard stones in top 25 cm</td><td>Planting miscanthus on soils less than 30 cm (Grade 3a) is unlikely to be viable due to restriction of root growth, higher risk of lodging
Miscanthus can tolerate stony soils if there is sufficient depth, but higher stoniness will hamper planting; limiting viability beyond 3b for stoniness. Some evidence suggests a certain degree of stoniness may improve performance on heavy clay soils, by improving aeration and water infiltration (Reinhardt et al., 2021)</td></tr>
</table>

[a] ALC guidance for flood risk is required for summer and winter, only summer flooding shown as example as flooding over the growing season is more likely to affect yield.

The ALC/MLCA classification systems were not intended to assess suitability of a specific crop to a particular field, merely to grade land based on general limitations to agricultural use. There is some debate as to the accuracy and practical utility of using the method in this way (Rollett & Williams, 2021). While most physical aspects of land classification can be considered relatively stable, climate criteria such as rainfall and interacting factors of flood risk, droughtiness and erosion can vary distinctly between years and are exacerbated by climate change. Changes in these climate criteria would likely cause some areas, arable areas in particular, to be reduced in grade (Keay et al., 2014). In addition, ALC grades often vary within field boundaries due to changes in soil quality, drainage or slope that can occur over small distances (Table 3). These differences affect decision-making on a field-by-field basis, but could present an opportunity for land sharing strategies and precision agriculture.

Spatial demand scenarios suggest biomass-producing catchments would require using a mixture of both arable land and grassland, the majority of which being grassland (Albanito et al., 2019; Lovett et al., 2014). Arable land covers 32% of the total area of England but only 3%–8% of Scotland, Wales, and N. Ireland (Table 4). Better miscanthus yields are predicted in the wetter, more westerly regions of England and Wales where grasslands predominate (Hastings et al., 2014; Shepherd, Littleton, et al., 2020) (Figure 1). In the east of England, where the bulk of arable land is located, periods of drought are becoming more frequent and longer in duration, which is already limiting agricultural production (Table 1). Climate change limitations to agricultural production in these areas are now less likely to be dominated by cold and wetness, and more influenced by drought risk, especially areas with low available soil water capacity (AWC) and high potential soil water deficit (PSWD; Rollett & Williams, 2021). In addition, increased flooding will prohibit planting and harvesting due to hampering vehicular access.

From a planning perspective, understanding the costs and benefits of planting on grassland is more complicated. Grasslands encompass a wide range of site and soil conditions, farming systems, management intensities, and habitats. Many grassland areas also include protected areas of high-conservation value which would be considered unsuitable and unavailable (JNCC, 2011). There is also a lot of variation in how UK grassland areas, especially semi-natural grasslands, are categorized, whether by habitat definitions, land classification systems, or DEFRA definitions that relate to broad farming practices. For example, whether farmland is open or enclosed, and whether grassland areas are temporary grass leys in an arable rotation or permanent grasslands (Tables 2 and 4). By DEFRA definitions, permanent grassland is any grassland area which has not been tilled and resown over the last 5 years, and temporary if they are less than 5 years old (DEFRA, 2023a). Temporary grassland often refers to grass leys, which if used in rotation with arable crops should be considered as being part of an arable system rather than permanent grassland (Richards et al., 2017).

Spatial studies provide a good overall indication of the potential planting area that could accommodate scaling up of miscanthus production. However, only a few account for the wider impacts on ecosystem services (Milner et al., 2016). Environmental factors that govern impacts of miscanthus establishment on ecosystem services are largely site specific and depend greatly on the previous land use (Whitaker et al., 2018).

3 | WHAT ARE THE MAIN ECOSYSTEM SERVICE IMPACTS TO BE CONSIDERED PRIOR TO SCALING UP?

The impacts of scaling up miscanthus production on GHG emissions and ecosystem services are key factors to consider prior to developing strategies for scaling up miscanthus production. Impacts of land use transitions to miscanthus will vary depending on the geographic location of the site (climate and soil type), previous land management (arable or grassland), the species and genotype of miscanthus established, and the length of time since the stand was established (McCalmont & Hastings, 2017; Richards et al., 2017; Whitaker et al., 2018). Key indicators include nitrous oxide emissions, soil carbon emissions, hydrological impacts, and biodiversity impacts.

3.1 | Nitrous oxide emissions

Nitrous oxide (N_2O) has a global warming potential 298 times greater than carbon dioxide (CO_2) which makes these emissions a significant factor in estimating the GHG impacts of any change in land use (IPCC, 2007). N_2O emissions from agriculture predominantly derive from N fertilizer applications, its release is stimulated by soil disturbance or compaction (Ferchaud et al., 2020; Holder, McCalmont, et al., 2019; Peyrard et al., 2017). Rates of N_2O emissions are controlled by microbial nitrification and denitrification processes which occur in the soil and are influenced by: soil water content, temperature, soil texture, pH and SOC content (Rees et al., 2013). N_2O emissions are known to vary significantly depending on prior land use (arable/grassland), historic and current fertilizer application rates and the length of time since establishment, with more N_2O emissions observed during establishment on grasslands than arable sites (Whitaker et al., 2018). The general consensus is that any short-term increase of N_2O emissions during establishment would be offset by reduced requirements of long-term fertilizer application and improved carbon sequestration over the lifetime of the crop, as N_2O emissions from miscanthus

TABLE 4 United Kingdom land cover by biodiversity broad habitat classification (Jackson, 2000). Including estimated land areas based on data from the CEH UK Land Cover Map 2021 (LCM2021; Marston et al., 2023). Data are presented as M ha and percentage (%) of total land area by region.

Land cover class	Biodiversity broad habitat classification	UK	England	Scotland	Wales	N. Ireland
Arable and horticultural	Covers arable cropland (including perennial, woody crops, and intensively managed commercial orchards, commercial horticulture land, freshly ploughed land, annual grass leys, rotational set-aside, and fallow	4.912 (20%)	4.187 (32%)	0.596 (8%)	0.084 (4%)	0.045 (3%)
Improved grassland	Broad habitat characterized by vegetation dominated by a few fast-growing perennial grass species such as *Lolium* spp. and white clover (*Trifolium repens*). Typically grown on fertile neutral soils, improved grasslands are typically either managed as pasture or mown regularly for silage production. They are periodically resown and maintained by fertilizer application and weed control	6.639 (27%)	3.930 (30%)	1.305 (17%)	0.777 (37%)	0.627 (44%)
Acid grassland	Characterized by dominance of grasses and herbs on a range of lime-deficient soils which have been derived from acid bedrock or superficial deposits of sands and gravels (pH <5.5). Includes a range of habitats from open communities of very sandy soils in the lowlands to closed pastures on red brown earths, to damp acidic grasslands typically found on gleys and shallow peats	2.187 (9%)	0.445 (3%)	1.228 (16%)	0.440 (21%)	0.074 (5%)
Neutral grassland	Broad habitat characterized by grasses and herbs on a range of neutral soils (pH 4.5–6.5). It includes enclosed dry hay meadows and pastures and a range of grasslands that are periodically flooded or permanently moist Unimproved, species-rich neutral grasslands are usually managed traditionally as hay meadows and pastures. Semi-improved are usually managed for pasture or for silage/hay. Neutral grasslands differ from improved grasslands by having less lush sward containing a more diverse range and greater coverage of herbs with <25% cover of perennial ryegrass (*Lolium perenne*)	0.420 (2%)	0.166 (1%)	0.011 (<1%)	0.053 (3%)	0.191 (13%)
Calcareous grassland	Characterized by dominance of grasses and herbs on well-drained soils formed from weathering of chalk/limestone or base-rich rock (pH >5). Contain a diverse range of grass and herb species distinctly different from neutral or acid grassland	0.256 (1%)	0.239 (2%)	0.003 (<1%)	0.001 (<1%)	0.013 (1%)

establishment are lower than those of arable crops or intensive grassland management (Krol et al., 2019; McCalmont & Hastings, 2017; Whitaker et al., 2018). In very N-limited soils, some N application may assist establishment, but for the majority of cases, this is not required, and annual applications are unnecessary to achieve respectable yields (McCalmont & Hastings, 2017). Strategic placement of stands might prevent N run-off or leaching and benefit miscanthus yields (3.3). An informed balance must be struck between rates of N fertilizer, soil fertility, miscanthus biomass yields, and profitability to growers, with the environmental impacts of GHG balances, nutrient off-take, and biomass quality implications (Ferchaud et al., 2020; Hodgson et al., 2010; Roth et al., 2015; Shield et al., 2014).

3.2 | Soil organic carbon stocks

Ninety-five percent of UK land carbon stock is held in our soils, and 40%–60% of organic carbon lost from arable soils is caused by intensive agriculture (DEFRA, 2022a). As part of the effort to reduce GHG emissions, long-term preservation and improvement of SOC stocks is an important mechanism of emission reduction and removal. SOC gains derive from inputs from miscanthus root biomass and, to a lesser extent, from decomposition of leaf litter (Bai & Cotrufo, 2022). However, these changes occur slowly over the crop's rotation (10–20 years) and gains can take decades to accumulate and stabilize (Qin et al., 2016; Rowe et al., 2016; Smith, 2004). As a result, there are higher SOC concentrations on land planted with perennial grasses than land planted with annual crops (Bai & Cotrufo, 2022). Better SOC gains can be expected over longer rotations on soils with a higher clay content, and lower gains on sandy soils (Bai & Cotrufo, 2022; Rowe et al., 2020). For this reason, the majority of field studies report variable results with trends of an increase or no change in SOC when miscanthus is established on former arable land, and a reduction or no change when established on grassland (Clifton-Brown et al., 2007; Dondini et al., 2009; Felten & Emmerling, 2012; Hansen et al., 2004; Holder, Clifton-Brown, et al., 2019; Nakajima et al., 2018; Poeplau & Don, 2014; Richter et al., 2015; Rowe et al., 2016; Schneckenberger & Kuzyakov, 2007; Zatta et al., 2014; Zimmermann et al., 2012).

Studies have noted variable impacts following reversion of miscanthus stands back into annual rotation (Dufossé et al., 2014; Martani et al., 2022; Rowe et al., 2020). Many studies examining SOC changes in response to miscanthus establishment highlight difficulties in making direct comparisons between field study data, due to the high variability of site conditions and the different experimental designs and sampling methodologies used (Agostini et al., 2015; McCalmont & Hastings, 2017; Rowe et al., 2016). Below-ground carbon balances are inherently more difficult to attain and are often based on a single-point or chronosequences rather than time-series observations (Agostini et al., 2015; Kravchenko & Robertson, 2011; Smith, 2004). Key sources of variability in field studies include differences in miscanthus stand age, the soil depth sampled, and whether soil bulk density changes were accounted for in the methodologies (Don et al., 2011; Ledo et al., 2020; Rowe et al., 2016; Ward et al., 2016). Initial soil carbon content has been suggested as a better indicator than previous land use when it comes to predicting SOC change. Rowe et al. (2016) identified an equilibrium point of 70 Mg C ha in the top 30 cm; soils with SOC above this point will likely lose carbon and those below will likely gain it. A spatial modelling study by Milner et al. (2016) also identified an equilibrium point based on modelled data, at the slightly higher value of 100 Mg C ha in the top 100 cm.

Miscanthus can root deeply, and miscanthus-derived C has been reported at 1.5 m depths (Felten & Emmerling, 2012). Few quantitative studies have been performed on the influence of miscanthus fine roots, their turnover, and the effect of root exudates to SOC dynamics and leaf litter contributions to the particulate C pool (Agostini et al., 2015; Al Souki et al., 2021; Ridgeway et al., 2022). Recent studies have identified significant variation between miscanthus species and genotypes in terms of their biomass partitioning, above and below ground, and how this relates to SOC accumulation (Briones et al., 2023; Ridgeway et al., 2022). Briones et al. (2023) identified that *M. sinensis* hybrid (Goliath) and *M. lutarioriparius* outperformed *M. x giganteus* in terms of increasing C storage in soils. The *M. sinensis* hybrid produced greater below-ground biomass and emitted less CO_2 than the other miscanthus species, suggesting a possibility to specifically breed for improved soil carbon sequestration traits (Briones et al., 2023).

3.3 | Hydrology

The water-use efficiency (WUE) of miscanthus, due to its C_4 photosynthesis and grass leaf morphology, is much higher than most arable crops grown in Europe, with WUEs ranging from 11 to 14 g dry above-ground biomass, per liter of water transpired, compared to 1–5 $g\,L^{-1}$ typical for barley, wheat, and maize (Clifton-Brown & Lewandowski, 2000; Mueller et al., 2005). However, to achieve higher biomass yields, miscanthus has a high-water demand which can affect the hydrological balance of soils (Clifton-Brown et al., 2002; Holder, Rowe, et al., 2019). When not irrigated, summer droughts have caused yield reductions of up to 40%–45% (Richter et al., 2008; Van der Weijde et al., 2017; Awty-Carrol et al., unpublished). Periods of both drought and flooding, often in the same locations between years, are becoming a more regular occurrence in many parts of the United Kingdom (Parsons et al., 2019). C_4 photosynthesis, the extensive deep root system and perennial nature of miscanthus species confers genetic advantages and variation in responses to water stresses that can be used to breed more drought or flood-tolerant varieties (Clifton-Brown et al., 2002; Clifton-Brown, Schwarz, et al., 2019; De Vega et al., 2021; Scordia et al., 2020).

Malinowska et al. (2020) conducted a study into relative yield across five miscanthus genotypes under drought conditions in a well-controlled pot experiment under glasshouse conditions. The study identified that sensitivity to water stress was better explained when leaf area and stomatal conductance data were included in their regression modeling, this varied substantially across the genus. *M. x giganteus*, in comparison to other genotypes, had a higher stomatal conductance, lower WUE in the well-watered control treatment and under drought conditions. Poor control of stomatal aperture in response to drought has previously been observed for *M. x giganteus* (Ings et al., 2013). Under drought conditions, above-ground yields for *M. x giganteus* declined significantly by 30%–35%, and like all but one of the genotypes studied, displayed greater below-ground biomass partitioning under water stress, possibly as a survival mechanism to either improving water scavenging or bolster rhizome resources ready for regrowth when the drought ends. An *M. x sinensis* genotype showed the greatest resilience to drought, more than doubling its water-use efficiency (WUE) compared to its well-watered control.

Field trials in Poland conducted by Clifton-Brown, Schwarz, et al. (2019) also highlighted *M x giganteus*' sensitivity to extreme drought. Very large soil moisture deficits across the 2015 growing season (>250 mm), more than 100 mm below the plant-available water in the soil profile, resulted in above-ground yields for *M. x giganteus* of less than 2 Mg DM ha^{-1}, five times lower than another miscanthus hybrid (GNT-10) which produced 11 Mg DM ha^{-1} in the same replicated plot trial and growing season (Clifton-Brown, Schwarz, et al., 2019).

However, drought-tolerant varieties, suitable for consistently water-stressed regions, may not necessarily provide the best yield performance in regions where water availability is intermittent and likely to be more variable over the lifecycle of the crop. A side-by-side replicated plot study conducted in Central Illinois, United States, compared miscanthus and switchgrass with a maize–soybean rotation. The study observed that while *M. x giganteus* displayed >100 mm more evapotranspiration than the other crops, this greater capacity to extract soil water could provide a measure of resilience where periods of drought are intermittent, but levels and periodicity of rainfall are sufficient to recharge soil water reserves (McIsaac et al., 2010). Malinowska et al. (2020) cautioned that, while yields for drought-tolerant genotypes may be superior under drought conditions, other genotypes, like *M. x giganteus*, might perform better in years where no water stress is experienced and might provide better overall yields over the whole 10- to 20-year rotation. Therefore, the mechanisms of drought resilience need to be considered carefully and characteristics of miscanthus genotypes and hybrids matched to specific soil and climatic conditions of the intended site.

For example, characteristics of large leaf area index, high level of rainfall interception, improved soil water infiltration, and greater capacity to extract soil water (ET) make certain miscanthus genotypes, like *M. x giganteus* very useful crops for land prone to waterlogging and inclusion as part of flood mitigation strategies (Holder et al., 2018; Holder, Rowe, et al., 2019). The dense, stiff-stemmed nature of mature miscanthus grass has been shown to provide a natural barrier, reducing particulates and run-off flow rates, and providing resistance to overland flows which make it useful as a flood defense measure by creating a leaky barrier (Holder, Rowe, et al., 2019; Shepherd, Clifton-Brown, et al., 2020). It has also been shown to survive flooding with little impact on yield under glasshouse and winter field conditions (De Vega et al., 2021; Kam et al., 2020).

Miscanthus has also been shown to be effective in controlling nutrient leaching (Cooney et al., 2022; Shepherd, Clifton-Brown, et al., 2020; Smith et al., 2013). Nitrate leaching is known to have significant negative impacts on water quality and freshwater and marine eutrophication. Under low N input scenarios, miscanthus has been shown to potentially reduce N leaching by up to 90% when compared to traditional annual cropping systems (McIsaac et al., 2010; Smith et al., 2013; Studt et al., 2021). Studt et al. (2021) conducted a study comparing N mineralization and leaching from soils under miscanthus and maize. During the establishment phase, no significant difference was observed in N leaching between maize and miscanthus, but when mature, miscanthus decreased N leaching by 42% under fertilized conditions (224 kg N ha^{-1}) and 82% when unfertilized (Studt et al., 2021). These characteristics make it a useful crop to include in water protection areas and as part of flood mitigation strategies, provided the variety used has a very low invasiveness risk to prevent escape along water courses (2.4) (Agostini et al., 2021; Ferrarini et al., 2017; Weik et al., 2022).

3.4 | Biodiversity

Biodiversity benefits of miscanthus stands are predominantly associated with the provision of over-winter cover, by improving the structural heterogeneity and connectivity within fragmented landscapes, via edge effects and creating wildlife corridors (Dauber et al., 2010, 2015; Dauber & Miyake, 2016; Manning et al., 2015; Semere & Slater, 2007a).

When miscanthus is planted in commercial monocultures, stands are densely planted with a low and open habit early in the growing season, rapidly increasing in height and density until canopy closure. Little light penetrates through the canopy, while this is beneficial for weed suppression and biomass yield, mature miscanthus stands present a less open and diverse understory when mature than short rotation coppice or forestry (McCalmont & Hastings, 2017). Miscanthus stands have been observed to have mixed effects in terms of diversity and abundance compared with annual crops or those of improved grasslands (Haughton et al., 2016; Semere & Slater, 2007b; Shepherd, Clifton-Brown, et al., 2020). Compared with mixed arable and grassland fields, miscanthus stands have been observed to contain lower species richness, biomass, and abundance of arachnids and ground beetles (Williams & Feest, 2019). A study found miscanthus had no effect on most pollinator groups studied compared with conventional crops on arable or grassland areas, and miscanthus was found to be beneficial in comparison to wheat and oilseed rape by improving species richness and abundance of less mobile solitary bee species, bumblebees, butterflies, and trap-nesting bees and wasps (Stanley & Stout, 2013). A study by Dauber et al. (2015) identified a positive correlation between “patchiness,” for example, gaps in the stand post-establishment, and increased biodiversity. The study observed that where gaps in the stand allowed light penetration, it resulted in higher activity density of epigeic arthropods, spiders, and ground beetles associated with the growth of non-crop vegetation (Dauber et al., 2015). Greater species diversity of small mammals and birds has been identified in the borders of miscanthus fields rather than within stands (Semere & Slater, 2007a).

Stands of miscanthus act as important refuges, for mammal species such a brown hare (*Lepus europaeus*). Although the crop itself, once mature, is of limited value as a food resource for most herbivore species, positive impacts are also dependent on availability of food resources in the surrounding landscape (Petrovan et al., 2017).

A small number of studies have reported that miscanthus stands may act as a disease vector or refuge for insect herbivores such as the Hessian fly (Mayetiola destructor), western corn rootworm (Diabrotica virgifera LeConte), and multiple species of Aphididae (Homoptera) and Thripidae (Thysanoptera), some of which are known carriers of wheat diseases (Spencer & Raghu, 2009; Stefanovska et al., 2017). While none of these disease or pest problems have been reported in UK miscanthus stands, it is likely that if the planted area increases, so will pest and disease pressure (Jørgensen, 2011). Continual monitoring and assessment will be required to inform risk assessments.

Studies on the effects of bird species and populations have identified that the number and density of birds using miscanthus stands are comparable with that of other conventional crops, but species composition has been observed to change from open field to scrub/woodland species as the crop grows in height and density over the summer months, with fewer birds seen in miscanthus stands over the winter (Sage et al., 2010). The rapid growth and structural change of the stands over the growing/breeding season may have temporary positive benefits over summer, but those benefits may diminish over winter for bird species associated with open farmland, although careful siting of stands to maximize edge effects could, however, limit these impacts (Bellamy et al., 2009; Sage et al., 2010).

While *M. x giganteus* genotypes present little invasiveness risk due to being a sterile hybrid with low rhizome spread, some *M. sacchariflorus* and *M. sinensis* genotypes have the potential to become more invasive (Bonin et al., 2014, 2017; Jørgensen, 2011; Lambertini, 2019; Perrier et al., 2019; Pittman et al., 2015; Raghu et al., 2006). A study by Perrier et al. (2019) found that a more invasive genotype of *M. saccariflorus* had been planted accidentally among stands of *M. x giganteus* at several field sites in France, assumed to be the result of misidentification of plant material by commercial nurseries (Perrier et al., 2019). A US study suggested a 5-year control window exists to manage and prevent any invasive spread by containing and eradicating any escapes (West et al., 2017). However, multilocation field trials under northern European growing conditions (EMI, OPTIMISC and GRACE) observed a minimal risk of invasiveness even when fertile flowering hybrids were included, due to low dormancy, poor overwintering and low seedling competitive strength (Clifton-Brown, Schwarz, et al., 2019). Varieties used to upscale production should be chosen to have as low an invasiveness risk as possible and necessary guidance and/or control measures must be put in place to further reduce invasiveness risks while upscaling UK production (Pittman et al., 2015; West et al., 2017).

4 | WHAT ARE THE BARRIERS AND INCENTIVES FOR SCALING UP PRODUCTION FROM A FARMERS' PERSPECTIVE?

Ultimately, the areas and locations where miscanthus stands are established will be determined by farmers and land managers, driven by economic advantage, market demand, and confidence in the stability of supply chains (Clifton-Brown et al., 2023; Ford et al., 2024). For this reason, many land area restrictions will likely be self-applied. For example, it is unlikely that a farmer would opt to plant miscanthus on their better quality land (ALC 1-3a), unless miscanthus achieved a much higher price, far greater savings, or provided additional benefits than a conventional crop, as evidenced by the slow uptake of miscanthus to date (Adams & Lindegaard, 2016). It has been suggested that the framing of marginal land itself may have acted as a disincentive, having failed to take into account of the personal and cultural values of farmers who take offence at the idea their land is "marginal" and therefore do not consider energy crops as an appropriate option for their land (Helliwell, 2018). Land ownership is another major barrier to uptake; 30%–40% of UK farms are tenanted, with the average tenancy lasting less than 4 years (CCC, 2018b). This significantly affects the number of farmers likely to establish a crop with a high upfront cost and a 15- to 20-year rotation length if they are unlikely to realize the benefits of having done so.

To date, establishment of miscanthus has predominantly been driven by development of large-scale biomass electricity generation, associated supply contracts, and historic establishment grants (Adams & Lindegaard, 2016; Clifton-Brown et al., 2023). There have not been establishment grants since 2013, previous initiative schemes have been criticized for failing to provide cohesive support to the industry along the whole supply chain at the same time, leading to a widening gap between policy aspirations and commercial reality (Adams & Lindegaard, 2016; Ford et al., 2024). It is not yet clear whether any more significant incentives will be provided for biomass crops via the recently introduced Environmental Land Management Scheme (ELM) that has replaced the basic payments and countryside stewardship schemes (Scott, 2024). From a financial perspective, longer term contracts were reported to encourage uptake and spread financial risk, but high transportation costs prohibited supply of material beyond the local area and a need for more diversified markets, perceived by farmers as reliable, has been highlighted (Ford et al., 2024; Von Hellfeld et al., 2022). In addition to its use as a combustion feedstock, miscanthus is also marketed and sold as an animal bedding material (Winkler et al., 2020). As bedding material is a reliable and established market, this option may offer reassurance to farmers looking to diversify and could help incentivize scale-up of domestic biomass supply. Multipurpose use of miscanthus biomass may also provide additional incentives to establish miscanthus stands in regions currently outside biomass power station catchments where the biomass may provide an economical alternative to cereal straws currently used for bedding, potentially freeing up more straw biomass for use in BECCS instead (Yesufu et al., 2020).

Lack of knowledge regarding how best to include miscanthus stands within farming systems has been cited as another potential barrier to wider uptake (Winkler et al., 2020). Surveys conducted on farms in England and Wales already growing miscanthus, reported improved profit margins due to reduced workload, reduced need for hired labor, and lower input and maintenance requirements (Glithero et al., 2013; Shepherd, Clifton-Brown, et al., 2020; Von Hellfeld et al., 2022). The crop was reported to grow particularly well on wet heavy soils, proved effective at reducing soil erosion when planted on sandy soils, and was found to make better use of smaller, odd-shaped fields or those with obstructions that prevented use of larger equipment such as spray booms (Von Hellfeld et al., 2022). A reduced requirement for spraying was also seen as beneficial by many farmers, especially on areas of land adjacent to dwellings and recreation areas. However, from a planning perspective, planting miscanthus stands adjacent to urban areas could present a potential fire hazard, due to the higher risk of fire from accidents or arson (Forestry Commission, 2023; Jørgensen, 2011).

5 | THE BENEFITS, CHALLENGES, AND TRADE-OFFS OF UPSCALING MISCANTHUS PRODUCTION IN ARABLE AND GRASSLAND AGRICULTURAL SYSTEMS?

5.1 | Upscaling on arable land

Planting miscanthus on arable land has been shown to have more potential benefits in terms of biomass yield, soil quality, GHG emissions, and biodiversity than planting on permanent grassland (McCalmont & Hastings, 2017; Whitaker et al., 2018). ALC grade 3 areas are more likely to have more favorable soil, climate, and management conditions, such as lower gradient, fewer obstructions, and easier access for harvesting machinery (Table 3). Higher biomass yields mean more carbon is sequestered from the atmosphere, more fossil fuels potentially displaced, and more carbon stored via BECCS. Better growing conditions and soil depth also allow more carbon to be stored below-ground via roots and leaf deposition. SOC is predicted to increase or remain stable over a miscanthus rotation, principally due to the avoidance of annual tillage (3.2). SOC gains are more likely on arable land with an SOC content ≤70–100 Mg C ha in the top 30 cm (Milner et al., 2016; Rowe et al., 2016, 2020). There is also increased likelihood of biodiversity gains when miscanthus is established in less-biodiverse, intensively managed arable areas due to increased structural heterogeneity, edge effects, provision of over-winter cover and improving landscape connectivity (Dauber et al., 2010; Dauber & Miyake, 2016; Haughton et al., 2016).

The main challenge presented by upscaling miscanthus production on arable land is the likelihood of competing with essential food production. UK arable land represents only 20% of the total land area, hence the arguments for restricting miscanthus production to more marginal areas (Marston et al., 2023; Valentine et al., 2012). The main trade-off is whether it is more beneficial, in economic and carbon terms, to use a smaller area of higher yielding land in closer proximity to end users or use a larger area of lower yielding land potentially further from end-use markets (Delafield et al., 2023). The economics and energy balance favor upscaling on land in closer proximity to biomass power stations or other centers of high demand (Albanito et al., 2019). Miscanthus-burning power stations were designed to burn cereal straws and are co-located in the United Kingdom's main arable farming regions: the East of England and the Midlands (Figure 1). Most of the land within a 40-km radius of these power stations is not currently classified as marginal. A potential trade-off could be to focus use of miscanthus as animal bedding and free up more straw for use as a biomass feedstock in these regions (Yesufu et al., 2020).

Another challenge to upscaling miscanthus in the east of England are droughts caused by climate change (Parsons et al., 2019). Many arable areas currently considered within ALC grade 1–3 may become classed as marginal due to changes in climate (2.2.3). Economic modelling has estimated that a winter wheat yield reduction of 10%–30% could be sufficient to make miscanthus a financially optimal alternative (Glithero et al., 2015). This presents both a challenge and an opportunity for miscanthus as summer droughts can cause yield reductions in some genotypes (Richter et al., 2008; Van der Weijde et al., 2017).

However, the wide range of genotypes and morphologies within the miscanthus genus, coupled with its perennial nature and capacity to produce deep roots, provides great potential for breeding drought resilient, or even tolerant, varieties that could be deployed in locations where food crop yields become unsustainable without uneconomical levels of irrigation (Clifton-Brown et al., 2002; De Vega et al., 2021; Scordia et al., 2020).

Yield decline in arable areas has also resulted from prevalence of herbicide-resistant weed species such as blackgrass (*Alopecurus myosuroides*), which presents a persistent problem in the south-east of England and has been spreading northward (Glithero et al., 2013). A trade-off could be to strategically plant miscanthus in affected areas as a means of biological control. The specific effectiveness of miscanthus as a blackgrass control has not been extensively trialed, but use of fallowing or grass leys has been shown to reduce blackgrass seedbanks by 70%–80% per year (Moss & Allen-Stevens, 2018); miscanthus, also a perennial grass, would likely provide the same function.

If miscanthus is upscaled on arable land, the benefits of doing so must outweigh the costs, and strategies must be employed to mitigate any potential negative impacts. The benefits that can be achieved by establishing miscanthus on arable land predominantly derive from its perennial nature and longer rotation length compared to annual crops, due to reduced inputs and avoidance of regular tillage and traffic over the site. As the crop requires little or no maintenance besides establishment and harvesting, benefits predominantly result from providing a rest period for land that has been intensively managed, especially land that is displaying yield decline and/or soil fatigue, and potential for reducing nutrient leaching into water courses. Within an arable context, a miscanthus stand could be considered as a longer term fallow or grass ley, with the production of plant biomass over the rotation as opposed to livestock, but potentially at significantly lower cost, inputs, labor requirements, and GHG emissions (Glithero et al., 2013; Shepherd, Clifton-Brown, et al., 2020; Von Hellfeld et al., 2022). Eliminating annual tillage and nutrient applications would allow soil carbon stocks to gradually replenish from root turnover and leaf litter inputs, something that is being further developed by the breeding of deeper-rooting varieties (Briones et al., 2023).

5.2 | Upscaling on grassland

If sufficient domestically sourced biomass is to be produced to meet potential BECCS targets, it is likely that conversion of substantial areas of grassland to biomass crops will be required (Albanito et al., 2019). Grasslands represent 39% of the total UK land area and comprise the majority of lower ALC grades 3b-5 (Table 2; Marston et al., 2023). Grasslands cannot be considered as a single category of land use as they encompass a wide range of site and soil conditions, farming systems, management intensities, and habitats (Table 4). Upscaling miscanthus production on improved pastureland or semi-natural/rough grazing areas presents different benefits, challenges, and trade-offs (Table 5). Large grassland areas in the west of England and Wales are predicted to support high yields of miscanthus, resulting from the predicted increase in temperature and rainfall (Table 1; Hastings et al., 2014; Shepherd, Littleton, et al., 2020).

The main environmental benefits of growing miscanthus on grassland are reduced emissions, improved

TABLE 5 Comparison of the main costs, benefits, and trade-offs of upscaling miscanthus production in arable and grassland agricultural systems.

Land use and predominant ALC grade	Yield	Ease of management	GHG/C	Biodiversity	Climate change impacts	Agricultural systems impact	Mitigation measures
Arable rotation (including temp grass ley/fallow) ALC 3a	• Higher yields • More favorable soil and climate characteristics. • Greater likelihood of proximity to high-demand centers	• Lower slope & likely fewer obstructions • Good access and use of harvesting machinery • Possible option for weed control (blackgrass)	• More carbon sequestered • SOC predicted to increase or remain stable over miscanthus rotation • Higher SOC gains in clay soils, lower in sandy soils	• Higher gains in less-diverse intensively managed areas • Improves structural heterogeneity & landscape connectivity	• Moderate risk of drought and/or flood depending on location • Risks offset by matching genotype to site conditions • Reduced soil erosion & run-off flow rates	• Potential displacement of food crop production • Dependent on economics of production and market availability	• Plant on sites as long-term break crop for sites displaying yield decline; either due to soil fatigue or persistent weed problems
Impr oved Grassland (ALC 3b-4)	• High to moderate yield • Dependant on soil and climate characteristics	• High to moderate. • Steeper slopes and poorer access may hamper mechanical harvesting	• Carbon sequestered proportional to yield • SOC predicted to remain stable or decrease over miscanthus rotation • High C peatland must be avoided	• Higher gains in less-diverse intensively managed areas • Improves structural heterogeneity & landscape connectivity	• Moderate to high risk of drought and/or flood • Reduces run-off flow rates. Potential use in flood mitigation measures	• Potential displacement of livestock production • Dependent on economics of production and market availability	• Incorporate as strips and buffers to increase productivity, biodiversity, erosion, and flood mitigation • Alternative use as animal bedding may offset financial risk
Rough grazing (semi-natural) (ALC 4–5)	• Lower yield. • Poorer soil and climate characteristics • Reduced likelihood of proximity to high-demand centers	• High slope and increased chance of obstructions • Severe limitations to access and mechanical harvesting	• Lower carbon sequestration • SOC predicted to remain stable or decrease over misc. rotation • More likely to contain high C peatland or very shallow low-C soils	• Establishing on areas of high species diversity would likely be detrimental to biodiversity	• Higher risk of flood • Higher risk of lodging, exposure, and killing frost in uplands • Potential use in flood mitigation measures to reduce run-off flow rates	• Less chance of significant impact on livestock production • More likely driven by local markets or environmental benefits (e.g., buffers)	• As improved grassland above

water quality, and flood management (De Vega et al., 2021; Holder et al., 2018; Holder, Rowe, et al., 2019; Kam et al., 2020; Shepherd, Clifton-Brown, et al., 2020; Weik et al., 2022). Miscanthus requires fewer chemical inputs than intensively managed pastureland (McCalmont & Hastings, 2017). Studies have highlighted the benefits of establishing miscanthus in nitrate vulnerable zones or areas where substantial N runoff or leaching presents a persistent problem (Cooney et al., 2022; Studt et al., 2021). As miscanthus is harvested in late winter/early spring, the crop is still standing throughout the wetter and windier months. Use of miscanthus in integrated riparian buffer zones in grassland areas has been suggested as a way of providing multiple benefits to water quality, biodiversity, and profitability (Christen & Dalgaard, 2013; Ferrarini et al., 2017; Zak et al., 2019; Winkler et al., 2020; Agostini et al., 2021).

The main challenges associated with upscaling miscanthus production on grassland areas are ensuring conservation of biodiversity and soil carbon stocks, and potential competition with livestock production. As with arable land, biodiversity gains from including miscanthus are associated with improving structural heterogeneity and connectivity of fragmented landscapes (Dauber et al., 2010; Dauber & Miyake, 2016; Haughton et al., 2016). However, biodiversity gains are only likely when miscanthus is planted on intensively managed or improved grassland sites. Semi-improved or unimproved grasslands contain a wide array of important species that provide many essential ecosystem services (Jackson, 2000). Semi-natural grassland areas have been in decline in the United Kingdom, 47% were lost between 1960 and 2013, predominantly due to conversion to improved grasslands or arable cultivation (Ridding et al., 2015). Large-scale planting of miscanthus on semi-improved or unimproved grassland areas with high species diversity would inevitably lead to biodiversity loss and planting large areas would therefore not be appropriate. Semi-natural grasslands, especially acid grasslands, also contain areas of high-carbon peatland that are also essential to maintain (Humpenöder et al., 2020). Semi-natural or rough grazing areas (ALC 4–5) can also present greater practical challenges in terms of steeper land gradients, limiting growth conditions, and significant limitations to access and harvesting (Tables 3 and 5).

In terms of maintaining soil carbon stocks, permanent grasslands tend to have higher initial SOC content than arable land due to the continuous cover of perennial grasses that facilitates carbon accumulation over multiple years without annual tillage (Bai & Cotrufo, 2022; Ward et al., 2016). The ecosystem and land-use model (ELUM) predicted significant SOC losses when miscanthus is planted on grasslands soils, even after areas containing >30% soil carbon were excluded from the model (Richards et al., 2017). However, to put this in perspective, based on conversion of grassland areas over a 35-year period, the ELUM model predicted that establishment of miscanthus would result in a lower SOC loss (45 Mg CO_2e ha^{-1}) compared to the alternative bioenergy crops: short rotation coppice, wheat, sugar beet or oil seed rape (70, 85, 119, & 120 Mg CO_2e ha^{-1}, respectively), only short rotation forestry was predicted to result in a lower SOC loss (24 Mg CO_2e ha^{-1}; Richards et al., 2017).

Using a similar spatial model, Milner et al. (2016) identified that when all areas containing histosols (high SOC, peaty areas) were excluded from the model, mean changes in SOC under miscanthus were found to be positive and some improved grassland areas showed greater increases in soil carbon compared with arable and forest soils (Milner et al., 2016). The initial SOC content, above or below 70–100 Mg C ha, is the best indicator of potential SOC loss or gain (3.2) (Milner et al., 2016; Rowe et al., 2016). Some studies have suggested that SOC losses may be recovered during the lifetime of the crop and GHG emissions could be further reduced by adopting lower impact establishment regimes (Cooper et al., 2021; Holder, McCalmont, et al., 2019; McCalmont & Hastings, 2017).

Any initial carbon losses from the soil during establishment need to be balanced against the amount of C sequestered and captured either in the soil, or at end use in the case of BECCS. If BECCS is the end use, a net negative carbon balance could still be achieved despite initial soil carbon loss following miscanthus establishment (Albanito et al., 2019). For these reasons, miscanthus is likely to provide more benefits and fewer drawbacks when planted on more intensively managed, improved grassland sites used for pasture or silage production that are periodically resown. These areas often have substantially lower carbon soils than less intensive or extensively grazed grasslands (Ward et al., 2016). Again, this comes into potential competition with food production. The CCC pathways have considered the possibility of a longer term trend of reduced meat and dairy consumption and infer this trend may increase land availability for production of alternative crops (CCC, 2020). However, this is predicated on some major assumptions of long-term behavioral change and assumes any reduction in domestic consumption would not focus production toward export markets instead, as a substantial proportion of UK animal products is already exported (DEFRA, 2022b).

As with arable production, there may be a tipping point where miscanthus production becomes more economically advantageous compared to the existing livestock farming systems, or a good potential diversification option for a proportion of the land holding. Between 2018 and 2021, approximately 16% of mixed farms, 36% of grazing livestock farms, and 10% of dairy farms in England made a loss from the agriculture side of their businesses, as their costs of production outweighed the value of their output (DEFRA, 2022a). If perceived as a legitimate alternative crop, miscanthus could provide a diversification option for these farms.

Miscanthus stands do not have to be a whole-field replacement, establishing strips or alleys and utilizing areas of land that are otherwise awkward to manage could present suitable areas to establish smaller stands; provided those areas have suitable access, slope and microrelief to enable harvesting (Von Hellfeld et al., 2022). While larger field sizes lead to greater economies of scale, it has been shown that smaller plantations of less than 1 ha can provide reasonable gross margins and make use of 5 m wide buffer zones besides water courses where fertilizer applications are prohibited (Winkler et al., 2020). Strategically situating miscanthus stands or planting in strips has been suggested as a useful mechanism to help buffer against nutrient runoff and soil erosion (Agostini et al., 2015; Anejionu & Woods, 2019; Weik et al., 2022).

Miscanthus established in large grassland areas in the west of England and Wales for commercial scale energy production would currently be subject to increased costs and emissions due to additional haulage requirements required to transport biomass to distant power stations. However, these are the UK regions where miscanthus is predicted to be more productive (Table 1) and CCUS hubs are planned in these regions (Figure 1; BEIS, 2018; Hastings et al., 2014; Shepherd, Littleton, et al., 2020). Creation of more local markets for bioenergy generation in grassland regions in close proximity to these planned CCS hub sites would provide greater incentive for miscanthus establishment in these regions (Von Hellfeld et al., 2022). Pelletizing miscanthus would also allow its biomass to be used in a wider range of heat and power generators (Fusi et al., 2021; Hastings et al., 2017). Alternatively, animal bedding has been suggested as a trade-off which may prove a more attractive prospect for livestock farmers. For example, Wales imports five times more straw from England than it produces domestically for animal bedding (Copeland & Turley, 2008). This could assist in establishing potential supply chains while BECCS infrastructure develops, and/or allow for diversion of cereal straws from bedding to bioenergy. The LCA study performed by Yesufu et al. (2020) suggested that miscanthus use for bedding presented a significant market opportunity for farmers, and a promising option for indirectly reducing emissions, provided displaced forage was not replaced by concentrated feed and miscanthus could be integrated into those landscapes without exacerbating or displacing pollution loading from livestock production.

In summary, from an environmental perspective, establishing miscanthus on improved grassland areas would likely result in greater benefits and fewer drawbacks than establishing on semi-natural grassland areas. This is due to the greater risk of negative impacts biodiversity and SOC, as well as the potential logistical restrictions and yield reductions of establishing miscanthus on ALC grade 4–5 land. Establishing miscanthus on improved grasslands would in effect be substituting one perennial grass species with another, exchanging *Lolium* for miscanthus. The benefits of doing so would include lower requirements for inputs, labor and maintenance compared to *Lolium* grown for livestock production, and potentially come with lower costs and fewer environmental impacts. However, upscaling miscanthus production in these areas would need to be attractive to farmers, practically and economically. Changes in land use must also avoid direct and indirect effects of displacement of livestock production, either within the United Kingdom or off-shore. The trade-offs could be to incentivize multipurpose land use strategies such as establishment of miscanthus as strips/alleys and buffer zones within fields, and raising awareness of the potential use of miscanthus, not just as a combustion feedstock, but also as an animal bedding material. Spent bedding may also be subsequently used as a bioenergy feedstock via anaerobic digestion which could also assist in reducing emissions from energy generation.

6 | CONCLUSIONS

The debate over where and how much we should scale up miscanthus in the United Kingdom is contentious due to concerns over competing land use demands, the unfamiliarity of the crops and uncertainty over the location of future markets. To help inform this debate we present seven statements, strongly supported by the evidence presented, which underpin the development of a cohesive land management, energy, and emissions reduction strategy that can maximize the potential benefits and minimise any undersirable consequences of upscaling miscanthus production in the UK:

1. Sufficient areas of UK land have been identified as suitable for upscaling miscanthus cultivation. However, the availability of that land and farmers' inclination to grow the crop depends on land tenure, farmer willingness, and confidence in the stability of biomass markets.
2. Soil carbon benefits of miscanthus predominantly derive from its longer rotation length compared to that of arable crops. Loss or gain of soil carbon following transitions to miscanthus may be better predicted by initial

soil characteristics and SOC content than by broad land use classifications of former "arable" or "grassland" areas.

3. Ecosystem service impacts of miscanthus are highly site specific and are greatly influenced by soil characteristics, hydrology, and the position of stands within the landscape. These require assessment and planning on a site by site or end-use catchment basis.
4. Biodiversity benefits derive from provision of long-standing (overwinter) cover, creating structural heterogeneity in the landscape and connecting fragmented areas. Biodiversity gains are more likely when miscanthus is planted into more intensively managed landscapes with lower species richness and diversity. Miscanthus cultivation in areas of high biodiversity value, such as semi-natural grassland areas, should be restricted.
5. Use of smaller areas of more productive land situated closer to biomass power generators may have more benefits and fewer drawbacks in terms of GHG emissions and ecosystem services than using larger areas of less productive land that contain higher biodiversity and higher soil carbon stocks.
6. Strategies need to be developed to integrate miscanthus into farming systems in a way that is profitable, sensitive to local demand, climate, and geography that complements rather than competes with long-term food security by increasing overall farm profitability and resilience. These strategies could include:
   - Using miscanthus as a long-term fallow to help restore degraded and fatigued land, allowing recovery of SOC stocks, remediate soil compaction, weed pressure, and soil contamination. More field studies are required to assess the effectiveness of miscanthus as a weed control measure, ensuring that species/hybrids deployed do not in themselves present an invasive risk.
   - Planting miscanthus as buffer strips or strategically siting stands within the landscape can mitigate flood risk, run-off, erosion and improve water quality. More studies are required to identify optimum species, genotypes, and buffer designs to maximize co-benefits.
7. Consistent long-term policies, which support the whole supply chain, are required. These will be vital to ensure sufficient upscaling of miscanthus biomass to supply domestic production targets, and via BECCS, allow the United Kingdom to realize its ambition of achieving net zero emissions by 2050.

AUTHOR CONTRIBUTIONS

E. M. Hodgson: Conceptualization; data curation; formal analysis; writing – original draft. **J. McCalmont:** Conceptualization; writing – review and editing. **R. Rowe:** Writing – review and editing. **J. Whitaker:** Writing – review and editing. **A. Holder:** Writing – review and editing. **J. C. Clifton-Brown:** Writing – review and editing. **J. Thornton:** Writing – review and editing. **A. Hastings:** Writing – review and editing. **P. R. H. Robson:** Writing – review and editing. **R. J. Webster:** Writing – review and editing. **K. Farrar:** Conceptualization; funding acquisition. **I. S. Donnison:** Conceptualization; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during thecurrent study.

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