Received: 12 November 2018 | Revised: 31 July 2019 | Accepted: 13 August 2019

DOI: 10.1111/gcbb.12646

ORIGINAL RESEARCH

GLOBAL CHANGE BIOLOGY BIOENERGY

WILEY

Consequential life cycle assessment of miscanthus livestock bedding, diverting straw to bioelectricity generation

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Abstract

Straw is an important livestock bedding material facing increasing demand for alternative uses in Europe and is often transported long distances from arable to livestock regions. Alternative bedding materials cultivated directly on livestock farms could potentially avoid this transport and competition for use. For the first time, we applied consequential life cycle assessment (LCA) to account for the direct and indirect implications of miscanthus bedding production on livestock farms, considering displacement of fodder or livestock, and substitution of fossil fuels with straw in electricity generation. We modelled the effect of substituting straw with 'home-grown' miscanthus bedding across seven beef and sheep farms. The consequences of displacing grass forage (or animal) production with home-grown miscanthus bedding cultivation were evaluated via three farmer decision scenarios: buy extra concentrate feed (D_1), utilize remaining pasture areas more efficiently (D_2) and buy grass silage (D_3). Electricity generated from displaced straw (bedding) substituted either natural gas or coal electricity. Sensitivity analyses were undertaken using 34 scenario permutations to represent combinations of feed and electricity substitution, miscanthus fertilization rates and yields, and the quality of displaced pasture. Consequential LCA indicates that miscanthus bedding production could be environmentally beneficial, under scenarios involving D_2 and D_3. However, greenhouse gas emissions and wider environmental burdens may be increased under D_1 scenarios, owing to the environmental cost of additional concentrate feed production, and possible indirect land use change, outweighing the benefits from: (a) fossil electricity substitution with straw bioelectricity; (b) reduced animal emissions via improved digestibility of concentrate feed; (c) avoided straw transport. The ratio of the yield of miscanthus to replaced grass was found to be a critical determinant of D_1 environmental outcomes. We conclude that if grass forage production can be better managed, the use of miscanthus as a bedding material on livestock farms provides environmental benefits via diversion of straw to bioenergy use.

KEYWORDS
attributional LCA, biomass, digestibility, displacement, farm models, greenhouse gas, land use change, residue

1 | INTRODUCTION

European governments, through the Kyoto Protocol, have targeted a reduction in greenhouse gas (GHG) emissions to reduce effects of climate change (United Nations, 1998). Consequently, policies were created to foster the development of renewable energy. In December 2008, the Renewable Energy Directive was approved in the European Union, promoting energy generation from crops, wastes and crop residues (Suttles, Tyner, Shively, Sands, & Sohngen, 2014). Compared to other biomass sources, crop residues such as straw have low land use change (LUC) impacts and minimum competition with food and feed (Parajuli et al., 2014). Thus, straw, which is also used for animal bedding and soil improvement (Copeland & Turley, 2008), has become one of the most utilized sources of biomass energy in Europe (Parajuli et al., 2014).

The United Kingdom produces 9–10 Tg of cereal straw per annum (DEFRA, 2017). Straw for bedding is transported in bulk over considerable distances from arable producing areas to the livestock producing areas (Glithero, Wilson, & Ramsden, 2013b). For example, over five times more straw is imported from England into Wales for livestock bedding purposes than is produced in Wales (Copeland & Turley, 2008). This process is becoming increasingly unsustainable and uneconomical as the demand and price for straw increases (Wonfor, 2017). In 2017, straw prices rose due to poor harvest and increasing demand from new straw bioenergy plants (Driver, 2018).

Efforts by the livestock industry to address this issue have given rise to trials of alternative bedding materials such as woodchips, miscanthus, paper, bracken and reed canary grass among others (HCCMPW, 2010). Among these alternatives, miscanthus bedding is used because of its highly absorbent nature compared with other bedding materials and its usefulness in keeping the animals clean and warm (HCCMPW, 2010; Van Weyenberg et al., 2015). It can be cultivated on lower quality agricultural land than cereal straw, as is typical in regions where livestock are common, achieve good yields with low inputs and could supply farmers with enough bedding material for their livestock needs (McCalmont, 2018). Although commercially available miscanthus bedding (prepackaged) is currently more expensive than cereal straw (AHDB, 2018; HCCMPW, 2010), miscanthus bedding could be cost-competitive with straw bedding (Yesufu, 2019) and production of improved varieties, miscanthus seeded hybrids and seedling plug planting are likely to significantly reduce cultivation costs (Hastings et al., 2017). Some farmers have already expressed their interest in cultivating miscanthus on their farms to provide livestock bedding (W. Cracroft-Eley, personal communication, July 15, 2018). Thus, increasing demand and price of straw could drive the cultivation of miscanthus as a home-grown bedding material across livestock farms.

The adoption of home-grown miscanthus bedding on livestock farms alongside increased straw bioenergy generation could lead to significant farm-level benefits (Donnelly, Styles, Fitzgerald, & Finnan, 2011) and environmental credits from grid electricity substitution (Donnelly et al., 2011; Giuntoli et al., 2013; Nguyen, Hermansen, & Mogensen, 2013; Parajuli et al., 2014). However, growing miscanthus on livestock farms could displace animals and/or grass fodder (Donnelly et al., 2011). In addition to increasing emissions from feed production, potentially including indirect LUC (iLUC; Styles, Gibbons, Williams, Stichnothe, et al., 2015), feed displacement may affect farm-level emissions, as variations in diet composition to accommodate supplied grass feed or grain-based feeds could impact animal emissions by influencing digestibility (Jones, Jones, & Cross, 2014). Digestible feed is the portion of gross energy which is not excreted in animal faeces, therefore, any changes in digestibility and quality of feed will result in changes to animal emissions, which can be analysed using gross and net energy calculations incorporated into LCA models for livestock systems (IPCC, 2006; Soteriades et al., 2018).

Straw is used for liquid biofuel production (Wilson, Glithero, & Ramsden, 2014), in the mushroom industry (Copeland & Turley, 2008) and as a fuel for electricity generation (Powlson, Glendining, Coleman, & Whitmore, 2011). Straw bioenergy plants have increased in number over recent years (Farmers Weekly, 2017) with initiatives like the Contract for Difference fostering large-scale electricity production from straw by offering profitable rates for biomass plants compared to fossil and nuclear electricity (Hastings et al., 2017). Several studies have focussed on straw combustion for bioenergy and have concluded that it is more environmentally friendly than fossil fuels, and can mitigate GHG emissions via grid electricity substitution (Giuntoli et al., 2013; Lindorfer, Fazeni, & Steinmüller, 2014; Parajuli et al., 2014). It is likely, therefore, that there will be an increasing demand for straw for bioenergy purposes, leading to intense competition among straw-using industries (Glithero, Wilson, & Ramsden, 2013a).

There are two main categories of LCA, namely attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA). ALCA quantifies direct environmental burdens attributable to a production system or value chain across multiple stages of production and consumption (Plevin, Delucchi, & Creutzig, 2014). CLCA expands the boundaries of analysis to reflect direct and indirect changes associated with a particular intervention, in terms of stages and scales of production elsewhere (Yang, 2016). LCA modelling has been widely applied to analyse the environmental footprint of bioenergy from straw or miscanthus (Brandão, Milà i Canals, & Clift, 2011; Monti, Fazio, & Venturi, 2009; Nguyen, Hermansen, et al., 2013; Parajuli et al., 2014; Styles, Gibbons, Williams, Stichnothe, et al., 2015), more recently including consequential LCA to evaluate the wider environmental effects of bioenergy and agricultural system interventions (Plevin et al., 2014; Styles, Gibbons, Williams, Stichnothe, et al., 2015; Tonini, Hamelin, Wenzel, & Astrup, 2012; van Zanten, Bikker, Meerburg, & Boer, 2018). However, we are not aware of any published studies that have applied LCA to miscanthus as a bedding material, nor to consider the consequences of new bedding materials diverting straw bedding towards bioenergy generation. In this paper, we address those gaps and fully evaluate the potential net environmental impacts of alternative bedding.

2 | METHODS

2.1 | Goal, scope and boundaries

The objective of this study was to analyse the wider environmental consequences of cultivating miscanthus for bedding on livestock farms, considering possible displacement of forage grass feed or animals on livestock farms and diversion of straw (bedding) for bioenergy generation. We applied consequential LCA to evaluate the net environmental effects of simultaneous use of home-grown miscanthus for livestock bedding and straw for bioenergy, driven by declining costs of miscanthus as a cost-effective bedding material linked with increasing demand for straw from new bioenergy plants (reflecting renewable energy and GHG mitigation policies).

2.2 | Scope of LCA

Consequential life cycle assessment was undertaken for specific livestock farms requiring bought-in straw bedding, to evaluate the direct and indirect consequences associated with establishment of home-grown miscanthus for livestock bedding, diverting straw to bioelectricity generation and incurring multiple changes on the livestock farm (Figure 1). The reference flow and functional unit used was 1 Mg of dry matter (DM) straw bedding substituted. This represented the reference system functionality as bedding material. Changes in the system were calculated as environmental burdens and credits (avoided burdens), considered over a 20-year time period, representing the average miscanthus plantation lifetime, and were presented as environmental burdens or credits per Mg DM straw. The following relevant impact categories were analysed: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and resource depletion potential (RDP), based on CML (2010) life cycle impact assessment methodology (Table S4.1).

2.3 | Scenario permutations

As shown in Figure 1, the following main processes are involved in the CLCA chain of consequence: miscanthus bedding production, livestock feeding and manure management (MM), diversion of straw (bedding) to bioelectricity generation and substitution of conventional (coal or gas) electricity generation. In addition, for scenarios involving replacement of electricity generation from natural gas,

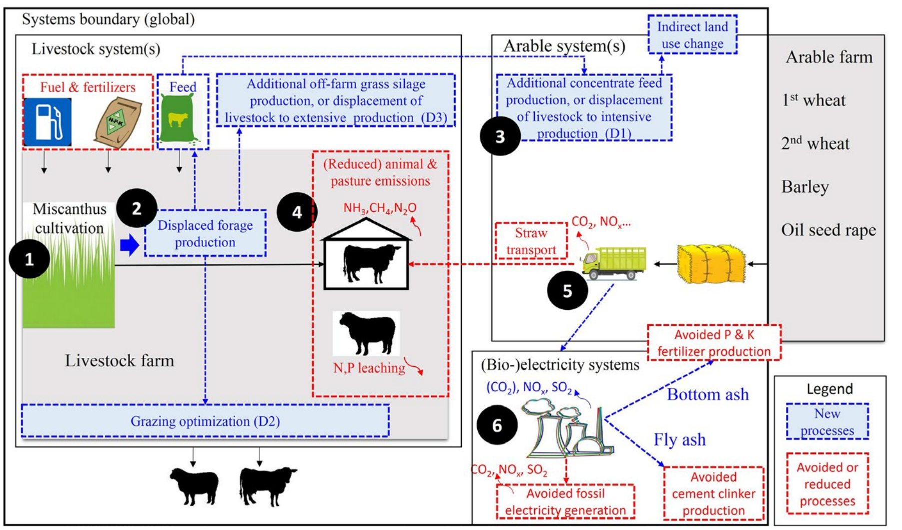

FIGURE 1 Flow chart of the chain of consequences arising from miscanthus substitution of straw bedding considered in the consequential life cycle assessment including, inter alia, miscanthus cultivation (1), displacement of animal (feed) production (2, 3), consequences for animal emissions on the livestock farm (4), diversion of straw for bioelectricity generation (5) and substitution of fossil-based electricity generation (6)

additional bottom ash generated by straw combustion can be returned to neighbouring arable land, replacing P and K fertilizers, and additional fly ash can replace cement clinker. Equation (1) below summarizes the series of changes captured in the CLCA.

$$\begin{aligned}\Delta\text{burdens} \\ &= [\text{miscanthus cultivation} + \Delta\text{pasture emissions} \\ &\quad + \Delta\text{feed production} + \left(\mathrm{D_1 iLUC}\right) + \left(\mathrm{D_1}\,\Delta\text{animal emissio} \\ &\quad + \text{straw transport to bioenergy plant} \\ &\quad + \text{straw combustion} + \text{ash disposal}] \\ &\quad - [\text{avoided straw transport to Wales livestock farm} \\ &\quad + \text{substituted grid electricity} \\ &\quad + \text{substituted fertilizer application} \\ &\quad + \text{substituted cement clinker}].\end{aligned} \tag{1}$$

Each variable is described in the sections below, but first we highlight the key factors that we varied in sensitivity analyses to generate a portfolio of scenario permutations that reflect the range of possible outcomes arising from use of home-grown miscanthus bedding on livestock farms (Table 1).

Many factors determine decision making on beef and sheep farms, limiting the accuracy of, for example, economic optimization modelling to determine likely outcomes (Ashfield, Wallace, Mcgee, & Crosson, 2014). Understanding the consequences of particular farmer decisions associated with establishment of home-grown miscanthus bedding production is in itself very useful. A particularly important effect within the chain of consequence is the potential displacement of grass fodder or animals on livestock farms arising from miscanthus cultivation. As elaborated below, we applied IPCC (2006) Tier 2 modelling of animal feed requirements and emissions according to three stylized farmer response decisions (S7).

D_1: The farmer purchases additional concentrate feed to compensate for reduced grass pasture production following miscanthus establishment, with possible iLUC driven by a marginal increase in concentrate demand (Figure 1). The D_1 management option modelled here represents a number of possible 'real' effects that may be incurred following the introduction of home-grown miscanthus bedding into livestock farms. It not only represents a farmer directly importing concentrate feed to replace grass feed lost on the farm but also represents the possibility of animals or meat production shifting to other farms in a process of livestock consolidation and intensification involving marginal production gains achieved through use of concentrate feed (Styles, Gonzalez-Mejia, Moorby, Foskolos, & Gibbons, 2018). The scenario not only functions at a farm level but also reflects a landscape scenario in which a small proportion of livestock farms specialize in miscanthus bedding production, displacing livestock to more intensive farms.

D_2: The farmer manages grazing better to compensate for displaced pasture by improving grass and grazing management, for example, through introduction of more tightly controlled rotational grazing, thereby avoiding the need to import more feed or other inputs onto the farm whilst maintaining farm-level productivity (Genever, Laws, & Frater, 2016). D_2 is also a proxy for a landscape scenario in which a small proportion of livestock farms specialize in miscanthus cultivation, whilst other farms sustainably intensify their production.

TABLE 1 A selection of tested scenario permutations representing different marginal effects, including fertilized or unfertilized cultivation of miscanthus (F_0, F_1) to replace straw bedding at a 1:1 or 2:1 dry matter ratio, leading to compensation of lost grass production by buying more concentrate feed (D_1), managing existing pasture more efficiently (D_2) or buying grass silage (D_3) in quantities influenced by grass digestibility (DE) of 55% and 65%. Diverted straw replaces either coal (Co) or natural gas (Ga) electricity generation. Scenarios 1, 27 and 34 represent best-case, most likely and worst-case scenarios, respectively, from a greenhouse gas mitigation perspective. All scenarios are detailed in Table S9.1

	Miscanthus bedding production		Welsh livestock farm effects			Diversion of straw
CLCA scenarios	Misc fert	Misc yield	Livestock farm response	DE% pasture	Substitution ratio	Marginal grid electricity
1. $F_0D_2$55%Co	0	6.81	D_2	55	1:1	Coal
2. $F_0D_3$55%Co	0	6.81	D_3	55	1:1	Coal
5. $F_1D_2$55%Co	52/9/74	8.73	D_2	55	1:1	Coal
12. $F_1D_3$65%Ga	52/9/74	8.73	D_3	65	1:1	Natural gas
17. $F_1D_1$65%Co	52/9/74	8.73	D_1	65	1:1	Coal
18. $F_1D_1$65%Ga	52/9/74	8.73	D_1	65	1:1	Natural gas
21. $F_0D_2$65%Co	0	6.81	D_2	65	1:1	Coal
27. $F_1D_3$65%Ga	52/9/74	8.73	D_3	65	1:1	Coal
34. $F_0D_1$65%2:1Ga	0	6.81	D_1	65	2:1	Natural gas

Abbreviation: CLCA, consequential life cycle assessment.

D_3: The farmer purchases additional grass silage to compensate for reduced pasture, with LUC driven by a marginal increase in demand for grass silage. This scenario also represents displacement of livestock from farms growing miscanthus bedding to more extensive farms elsewhere, at a farm or landscape scale.

From these responses we derived a series of 34 scenario permutations to integrate the range of direct and indirect effects arising in all of the affected systems (Table S9.1). Table 1 summarizes nine of these scenario permutations that illustrate the range of possible outcomes. Key variables were: farmer management decisions (D_1, D_2, D_3), iLUC for D_1, type of electricity generation avoided, different rates of digestibility (DE%) of the displaced pasture (that may be substituted with concentrate feed or imported silage, thus affecting animal emissions) and bedding substitution (Table 2). While we applied a farm-level modelling approach to accommodate data from seven livestock farms and elucidate the sensitivity

TABLE 2 Life cycle inventory data for all the marginal process changes arising in the chain of consequence, expressed for a reference flow of 1 Mg of dry matter straw diverted

Process/activity	Per year	Livestock farms range Min:Max values	
Farm inputs		Tables S1.1 and S6.1	
Direct effects		F_0	F_1
P losses	kg^{-1}	−0.09 to −0.005	−0.09 to −0.015
Net excretion (N_{ex}; D_1)[a]	kg^{-1}	−0.12 to −0.006	−0.09 to −0.005
Enteric CH_4 (D_1)[a]	kg^{-1}	−1.9 to −0.009	−1.6 to −0.003
MM CH_4 (D_1)[a]	kg^{-1}	−0.75 to −0.0008	−0.62 to −0.0007
MM N_2O (D_1)[a]	kg^{-1}	−0.0023 to −0.00001	−0.0017 to −0.00001
N_2O soils (D_1)[a]	kg^{-1}	−0.042 to −0.00002	−0.035 to 0.20579
Indirect effects			
Concentrate purchase (D_1)[b]	Mg DM concentrates	0.13–1.05	0.11–0.94
Farm optimization (D_2)[b]	—		
Grass silage purchase (D_3)[b]	Mg DM grass silage	0.13–1.2	0.11–1.06
Alternative straw use in arable region (bioenergy)			
Avoided transportation to livestock region[c]	tkm	300	
Transportation to power plant[d]	tkm	50	
Emissions[e]			
SO_2	g	578	
NO_x	g	1,615	
Bottom ash nutrient[e]			
Avoided P fertilizer	kg	1.4	
Avoided K fertilizer	kg	17.3	
Bottom ash disposal	kg	54	
Transportation to farm[d]	tkm	2.7	
Fly ash[e]	kg	7.1	
Transportation to cement factory[d]	tkm	0.35	

Abbreviation: MM, manure management.
[a]Calculated (IPCC, 2006).
[b]Livestock farm data.
[c]Wonfor (2017).
[d]Styles, Gibbons, Williams, Dauber, et al. (2015).
[e]Nguyen, Hermansen, et al. (2013).

of outcomes in relation to individual farm characteristics, the scenarios and associated narratives and results can be extrapolated to a landscape-level integration of miscanthus—for example, where a small percentage of livestock farms could convert to specialize in miscanthus bedding production to supply neighbouring farms, as described above. The most likely (Sc 27), best- (Sc 1) and worst- (Sc 34) case scenarios were extrapolated to a national scale by assuming that all straw used for bedding in the United Kingdom is substituted (6.2 million tonnes: Copeland & Turley, 2008). Results were normalized against EU per capita annual burdens (CML, 2010).

The following sections elaborate each of the key marginal changes in more detail. The life cycle inventory compiled for the full chain of consequences is summarized in Table 2.

2.4 | Miscanthus bedding production

Home-grown miscanthus was cultivated on the livestock farms, harvested annually, sun dried and used as bedding (step 1 in Figure 1). Miscanthus inputs and outputs were analysed for unfertilized (F_0) and typical fertilizer application (F_1) regimes with peak annual yields of 7.8 and 10 Mg DM/ha respectively (Donnelly et al., 2011; McCalmont, 2018; see Table S3.1). Annual NPK fertilizer application rates for the F_1 regime were 52/9/74 kg/ha. It was assumed that miscanthus reaches peak yield within 3 years and is productive for 20 years (Vyn, Virani, & Deen, 2012). The yield increase was 0%, 50%, 100% of peak yield for year 1, year 2 and year 3 to year 15. Yield decline was assumed to occur gradually, reducing by 5% every year from the 15th year (Hastings et al., 2017). There is some uncertainty about the quantity of miscanthus needed to replace straw bedding. If chopped and dried to moisture contents of 25% and below, miscanthus could replace straw bedding on a 1:1 basis (AHDB, 2018; Van Weyenberg et al., 2015). Preliminary studies on absorbency at Aberystwyth are suggesting that miscanthus could replace wheat straw by around 1.6:1 while some of the hardier, upland varieties bred at IBERS could be as low as 1.2:1 due to better texture and lower initial moisture content (M. Fraser, personal communication, October 2, 2018). Thus, we represented bedding replacement ratio within the sensitivity analysis by considering a baseline 1:1 or 2:1 Mg DM substitution ratio of miscanthus to straw bedding.

2.5 | Livestock farm system changes (including marginal feed production)

The introduction of miscanthus cultivation into livestock farms can have significant consequences for the extended livestock farm system, extending to feed supply chains (steps 2–4 in Figure 1). The following terms from Equation (1) pertain to livestock farm system changes (in brackets for D_1 scenario only): Δpasture emissions; Δfeed production; (iLUC); (Δanimal emissions).

Data from seven livestock farms were used to parameterize the CLCA and derive a range of plausible scenarios in terms of quantities of straw bedding displaced and animal husbandry impacts. These livestock farms were selected from 15 previously surveyed farms in Wales, based on use of straw bedding for sheep and cattle in the year 2012/2013 when they were surveyed (i.e. farms that produced their own straw or did not report use of bedding were excluded). These farms are fully described in S1 and Table S1.1, and were previously surveyed to assess the footprints of Welsh beef and lamb production (Hyland, Styles, Styles, Jones, & Williams, 2016), and attitudes and perceptions of Welsh farmers towards climate change (Hyland, Jones, Jones, Parkhill, Barnes, & Williams, 2016). All farm activities were modelled to account for animal emissions, fertilizer inputs, diesel and agrochemical use, feed imports, etc (Table 2), in order to capture any direct and indirect changes arising from the cultivation and use of miscanthus bedding on the farms. The quantity of miscanthus grown on each farm was based on the reported amount of straw bedding needed per year (Hyland, Styles, et al., 2016) and on the potential yield of miscanthus depending on the F_0 or F_1 fertilizer regime and miscanthus to straw substitution ratio (Table 1), that is, a farm requiring 12 Mg DM/year of straw bedding will require 2 ha of miscanthus producing 6 Mg DM/ha year (Table S5.1 in S5). Baseline farm operations were modelled according to activity data obtained from Hyland, Styles, et al. (2016) and farm-level emissions calculated using IPCC equations 10.23–11.11 (S6; IPCC, 2006).

The Δpasture emissions term (Equation 1) was calculated simply by calculating average fertilizer application per hectare of grass on each baseline farm, and subtracting fertilizer manufacture and application burdens for the number of hectares of grass replaced by miscanthus. Calculations of the Δfeed production, iLUC and Δanimal emissions terms (Equation 1; steps 2–4 in Figure 1) were undertaken as follows. Firstly, the quantity of grass feed displaced by miscanthus (step 2 in Figure 1) was calculated by estimating farm-specific livestock metabolizable energy (ME) intake per hectare of grass. This was estimated based on total ME requirements of animals on the farm, derived from productivity data and Tier 2 energy calculations (Hyland, Styles, et al., 2016; IPCC, 2006), minus ME supplied by feeds imported into each farm (Table S6.1; Hyland, Styles, et al., 2016). The potential displacement of grass fodder or animals on livestock farms was modelled as displaced feed ME (Table S6.1), leading to the possible farmer response decisions described above and listed in Table 1 (more detail in S7). Aggregate feed digestibility (DE%) was calculated for the baseline and miscanthus bedding scenarios to assess change in animal emissions (enteric methane and manure management emissions of methane, nitrous oxide and ammonia) attributable to the substitution of home-grown grass with concentrate feed (Table S6.2). These calculations are fully described in S6, along with soil and animal emissions.

2.6 | D_1 animal emissions

There is a reduction in animal emissions when extra concentrate feed is supplied and consumed by livestock, increasing the overall quality of the feed mix (IPCC, 2006). This was represented as an environmental credit compared to baseline animal emissions.

Indirect LUC for D_1 was calculated using Equation S2 (S7), based on Styles, Gibbons, Williams, Stichnothe, et al. (2015). For D_3, marginal grass silage production is most likely to occur through intensification of existing grassland with no change in soil organic carbon (IPCC, 2006; Styles, Gibbons, Williams, Stichnothe, et al., 2015), but incurs upstream burdens linked to fertilizer and energy inputs (Table S3.2). Options D_1 and D_3 are also proxies for the displacement of animal production to expanding intensive or extensive livestock farms respectively. Miscanthus and cereal straws break down readily and are composted easily (AHDB, 2018). Thus, it was assumed that nutrient release and emissions from the bedding component of manures would not be significantly altered following miscanthus substitution of straw. However, additional carbon sequestration is included for a 2:1 bedding substitution scenario to reflect the doubling of biomass being returned to soils in the bedding component of manures in this scenario (S4).

2.7 | Straw transport

Straw production on arable farms, within a representative UK 4 year rotation (S2), is not affected by the introduction of home-grown miscanthus bedding (Figure 1), and this step is therefore excluded from the CLCA. The produced straw is diverted away from long-distance transport to livestock farms in Wales ('avoided transport to Wales livestock farm' in Equation 1) towards a power plant for electricity generation located within 50 km of the arable farm ('straw transport to bioenergy plant' in Equation 1; step 5 in Figure 1).

2.8 | Straw bioelectricity generation

Modelling of straw bioelectricity generation (step 6 in Figure 1) was based on data from combustion of straw at the recently built Brigg Renewable Energy Plant located in Lincolnshire, UK (Brigg biomass, 2018). This 40 MW plant was commissioned in 2016 and consumes 250 Gg of biomass per year, consisting of oilseed rape straw, cereal straws and other biomass residues, with a net efficiency of 34% (Brigg biomass, 2018). Burdens arising from straw combustion (Equation 1) in a power plant were obtained from Parajuli et al. (2014). By-products of straw combustion include bottom ash and fly ash, which are recycled.

Bottom ash is a by-product of straw combustion, and contains P and K nutrients which can replace synthetic fertilizer (Nguyen, Hermansen, et al., 2013). Bottom ash was delivered back to the arable farm, incurring transport burdens, but avoiding application of synthetic P and K fertilizers based on the P and K content of bottom ash residues (Nguyen, Hermansen, et al., 2013; Table 2).

'Ash disposal' in Equation (1) is divided into two main fractions (Figure 1). Fly ash was transported 50 km to a cement factory (Table 2; Nguyen, Hermansen, et al., 2013) where it replaced cement clinker. 'Substituted fertilizer application' and 'substituted cement clinker' terms in Equation (1) were represented as avoided fertilizer and cement clinker manufacturing burdens taken from Ecoinvent (2010).

Bioelectricity generated by the diverted straw bedding replaces counterfactual marginal grid electricity generation by natural gas or coal ('substituted grid electricity' in Equation 1), reflecting the economic and policy factors influencing the grid mix in the United Kingdom, with coal used as baseline for this study (DECC, 2012; Styles, Dominguez, & Chadwick, 2016).

3 | RESULTS

3.1 | Climate change

Consequential life cycle assessment of the production of home-grown miscanthus bedding on livestock farms indicated that environmental outcomes were strongly influenced by a variety of both direct and indirect factors. The balance of emission consequences among the 34 scenarios ranged from a best-case abatement (net avoidance) of 1,454 kg CO_2e/Mg DM straw bedding replaced by miscanthus to a worst case of an emission increase of 1,414 kg CO_2e/Mg DM straw bedding replaced (Table 3). Note, full results for all 34 scenario permutations are presented in Table S9.1.

Climate mitigation was more likely to be achieved for scenarios involving the substitution of coal electricity generation by straw bioelectricity, and where displaced grass forage production was compensated by optimization of grass use (D_2) or importation of grass silage (D_3) to livestock farms growing miscanthus as bedding. Of the 34 scenarios evaluated, 24 showed a net reduction in GWP (including iLUC emissions). The default scenario that we consider most plausible under the current agri-economic conditions (Sc 27 in Table 3), involving grass silage as the marginal compensatory feed and coal electricity as the marginal substituted power generation, indicated a net GHG abatement of 260 kg CO_2e/Mg DM straw. Net GHG emission increases were more likely for scenarios

TABLE 3 Median results of net burden change across the seven farm systems, expressed per Mg DM straw displaced for scenario permutations summarized in Table 1, including cultivation of fertilized (F_1) or unfertilized (F_0) miscanthus that replaces straw bedding at a 1:1 or 2:1 dry matter ratio, leading to compensation of lost grass production by buying more concentrate feed (D_1), managing existing pasture more efficiently (D_2) or buying grass silage (D_3) in quantities influenced by grass digestibility (DE) values of 55% or 65%. Diverted straw replaces either coal (Co) or natural gas (Ga) electricity generation

CLCA		Global warming	Resource depletion	Eutrophication	Acidification
Scenarios		$kgCO_2e$	MJe	$kgPO_4e$	$kgSO_2e$
Sc 1	$F_0D_2$55%Co (Best case)	−1,454	−23,870	−1.22	−0.20
Sc 2	$F_0D_3$55%Co	−1,109	−22,154	1.25	1.97
Sc 5	$F_1D_2$55%Co	−1,371	−23,436	−0.79	0.22
Sc 12	$F_1D_3$65%Ga	−260	−8,617	2.44	3.67
Sc 17	$F_1D_1$65%Co	−601	−21,469	4.08	2.65
Sc 18	$F_1D_1$65%Ga	246	−7,961	5.40	4.45
Sc 21	$F_0D_2$65%Co	−607	−10,362	0.10	1.60
Sc 27	$F_1D_3$65%Co	−260	−8,617	2.40	3.70
Sc 34	$F_0D_1$65%2:1Ga (worst case)	1,414	−4,943	12.68	7.89

Note: Ranking of likely scenarios from most to least likely: 27, 2, 17, 5, 21, 1, 12, 18, 34.
Abbreviation: CLCA, consequential life cycle assessment.

where displaced straw bioelectricity replaced natural gas electricity generation and where displaced grass forage production was compensated by the purchase of additional concentrate feed (D_1; e.g. Sc 18 and 34 in Table 3). The average emission reduction for scenarios involving the substitution of coal electricity generation was 637 kg CO_2e/Mg DM straw replaced, while the average emission reduction for scenarios involving the substitution of natural gas was 117 kg CO_2e/Mg DM straw replaced (Table S9.1).

Burden increases involving the D_1 option were primarily driven by the cultivation and processing of crops used in the marginal concentrate feed, and iLUC that may be incurred through the associated expansion of cropland globally to meet the extra cropping demand (Figure 2a). The GWP balance for scenarios involving D_1 and natural gas displacement was positive (i.e. GHG emissions increased) if concentrate feed production incurred iLUC, but became negative without iLUC. This is because more GHG emissions were avoided from gas electricity generation than were incurred through the production of concentrate feed (without iLUC), with lesser emissions changes associated with straw combustion, straw transportation and management of ash, etc (Figure 2a; Sc 18 in Table 3).

3.2 | Resource depletion potential

In the default scenario (Sc 27), there was a net fossil resource saving of 8,617 MJe/Mg DM straw bedding replaced by miscanthus, ranging from 4,943 to 23,870 MJe/Mg DM under worst- and best-case assumptions (Table 3). RDP burdens were reduced in all scenarios, dominated by avoided fossil fuel electricity generation. Avoided natural gas (Sc 18, 34) and coal (Sc 17) electricity burdens were all greater than the incurred concentrate feed production burdens in D_1 scenarios (Figure 2b).

3.3 | Acidification and eutrophication

Acidification burdens generally increased following replacement of straw bedding with miscanthus (Table 3), but there were reductions of 0.2 and 0.3 kg SO_2e/Mg DM straw for scenarios 1 (Table 3) and 23 (Table S9.1) respectively. These scenarios involved unfertilized miscanthus cultivation (F_0), optimized grazing management (D_2) and substitution of coal electricity with straw bioelectricity. In all other scenarios, net acidification increases occurred due to the credits from avoided fossil fuel electricity generation being smaller than acidification burdens attributed to marginal production of imported concentrate (D_1) or grass silage (D_3) feeds, despite the comparatively high acidification burden of coal electricity generation (Figure 2d; Table S9.1).

Eutrophication potential results followed a similar pattern to AP results, as most scenarios (30 of 34) recorded burden increases except when straw replaced coal electricity and miscanthus cultivation led to grazing optimization (Sc 1 and Sc 5 in Table 3; Figure 2c). While miscanthus cultivation incurred AP and EP burdens from fertilizer manufacture and application, reductions in inputs of fertilizers and soil emissions on pasture areas within livestock farms led to slightly larger AP (Figure 2d) and EP credits (Figure 2c).

3.4 | Variation across livestock farms

Evaluating farm-specific results indicated a strong relationship between the relative yield of miscanthus compared with the yield of effectively utilized grass across individual farms on the one hand, and the net environmental burden or benefit incurred when miscanthus bedding displaces straw bedding on the other hand (Figure 3; Table 4). A low ratio of miscanthus:grass yield, due to high grass yield and effective utilization rate, results in large GHG emission increases across most scenarios, with the balance shifting towards even the most pessimistic (worst-case) scenarios achieving GHG mitigation at high ratios of miscanthus:grass yield (Figure 3). As shown in Figure 3, a 1:1 or 2:1 substitution rate of miscanthus to straw, with a 65% grass DE and natural gas electricity displacement resulted in net GHG emission increases attributable to straw bedding replacement on farms 1, 2, 3, 4 and 6, and net GHG abatement attributable to straw bedding replacement on farms 5 and 7 only. Home-grown miscanthus bedding production on farms 3, 5 and 7 drove net GHG abatement if grass digestibility was assumed to be poor (55%) rather than average (65%), reflecting greater animal-level GHG mitigation achieved by concentrate feed substitution of lower quality grass. When coal was displaced, all farms showed emission decreases, even with iLUC emissions for D_1 scenarios, except for farms 1, 2, 4 and 6 under a worst-case 2:1 substitution of miscanthus to straw with 65% grass DE.

3.5 | Scenarios extrapolated to national level

In 2007, straw bedding demand for livestock was about 6.2 million Mg of straw. In relation to the default CLCA scenario, replacing this quantity of straw bedding with home-grown miscanthus would lead to a GWP and RDP decrease of 1.6 million Mg CO_2e and 53 million Mg MJe, but an increase of 0.02 million Mg PO_4e and Mg SO_2e in EP and AP burdens respectively (Figure 4). Cultivating unfertilized miscanthus and optimizing pasture with coal displacement (best case: Sc 1) would lead to decreases of 9 million Mg CO_2e, 148 million Mg MJe, 0.007 million Mg PO_4e, 0.001 million Mg SO_2e in GWP, RDP, EP and AP burdens respectively. Figure 4 represents normalized burden changes for a national scenario of home-grown miscanthus bedding replacing all straw bedding across United Kingdom, for default (Sc 27), best-case (Sc 1) and worst-case (Sc 34) permutations. Normalized scores were highest for resource depletion and eutrophication burden changes, reaching a maximum normalized score increase of 2.77 million person equivalents (PE) for eutrophication under Sc 34 (Figure 4), mainly reflecting additional concentrate feed production (Figure 3). However, if farmers compensate for grass forage displacement by utilizing remaining grazing areas

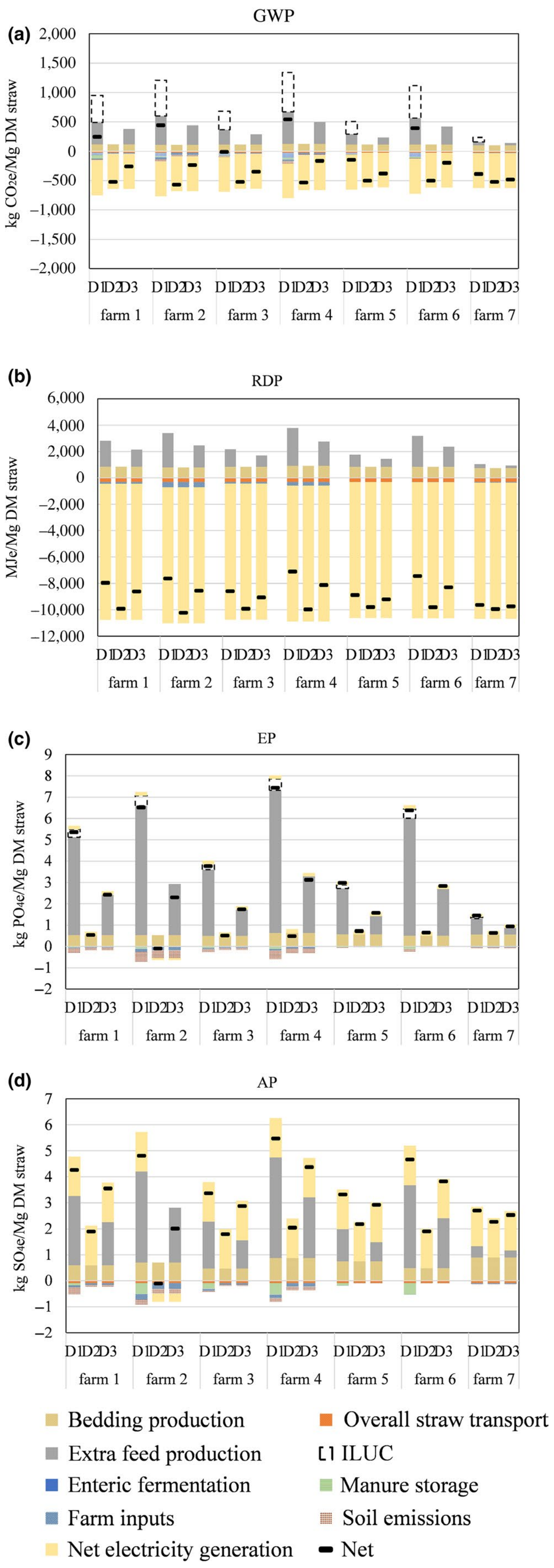

FIGURE 2 Net changes in (a) global warming potential (GWP), (b) resource depletion potential (RDP), (c) eutrophication potential (EP), (d) acidification potential (AP) per Mg DM, for F_1 (fertilized miscanthus) production under farm decisions D_1 (compensatory concentrate feed import), D_2 (grazing optimization), D_3 (compensatory grass silage import) and straw bioelectricity substituting coal (Table S9.1: Sc 10, 17, 27). All results are presented as changes relative to baseline straw bedding systems across all farms

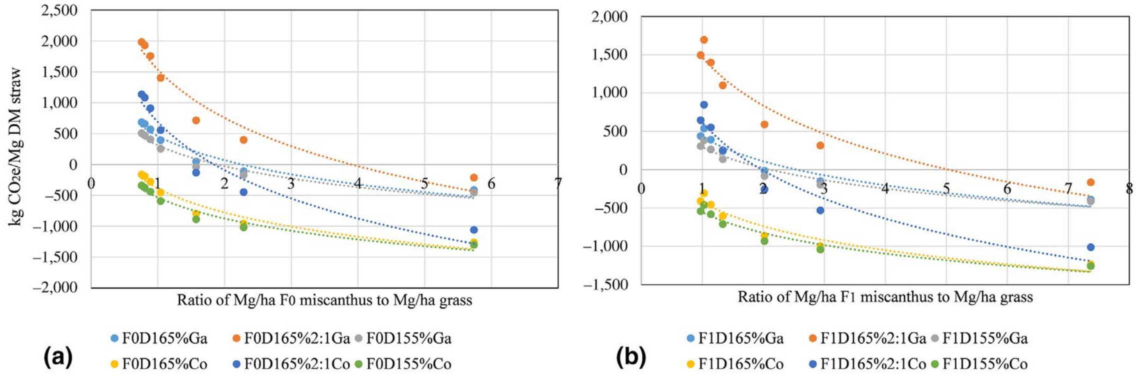

FIGURE 3 Net greenhouse gas change per Mg DM straw bedding substituted versus ratio of Mg DM/ha miscanthus yield to Mg DM/ha grass uptake by animals, for D_1 (with indirect land use change) permutations involving straw bioelectricity substitution of electricity generated by coal (Co) or natural gas (Ga) and digestibility (DE) of displaced grass forage production of 55% or 65%. Results shown for (a) unfertilized miscanthus (F_0) and (b) fertilized miscanthus (F_1). Dots represent the seven farms (from left to right: 2, 4, 6, 1, 3, 5, 7). Scenarios in graph correlate with D_1 scenarios in Tables 1 and 3

TABLE 4 Chart equations indicating the logarithmic relationships between greenhouse gas mitigation and the ratio of miscanthus to grass yields across the seven livestock farms under the concentrate feed purchase (D_1) permutations with indirect land use change, straw bioelectricity substitution of electricity generated from natural gas or coal, a 1:1 or 2:1 miscanthus to straw bedding substitution ratio and grass digestibility (DE) of either 65% (default) or 55%

	1:1 substitution	2:1 substitution	55% grass DE
F_0			
Natural gas displacement by straw + D_1	$y = -564\ln(x) + 461$	$y = -1{,}129\ln(x) + 1{,}537$	$y = -490\ln(x) + 313$
Coal displacement by straw + D_1	$y = -564\ln(x) - 386$	$y = -1{,}129\ln(x) + 690$	$y = -490\ln(x) - 534$
F1			
Natural gas displacement by straw + D_1	$y = -452\ln(x) + 424$	$y = -9051\ln(x) + 1{,}463$	$y = -389\ln(x) + 292$
Coal displacement by straw + D_1	$y = -452\ln(x) - 423$	$y = -905\ln(x) + 616$	$y = -389\ln(x) - 555$

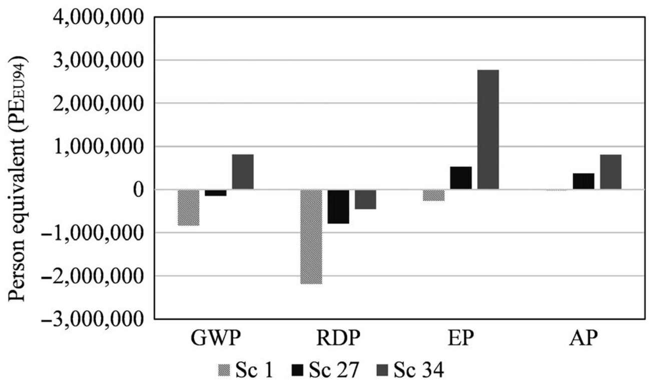

FIGURE 4 Net environmental loading changes for a national scenario in which miscanthus replaces straw bedding across UK livestock farms, expressed as normalized scores for best-case (Sc 1), most likely (Sc 27), and worst-case (Sc 34) permutations. Global warming potential (GWP), fossil resource depletion potential (RDP), eutrophication potential (EP) and acidification potential (AP) burdens were normalized against EU environmental loadings per capita (CML, 2010), results in 'person equivalent' (PE) units

more efficiently (Sc 1), the normalized score for eutrophication burden change drops to −0.26 million PE at the national scale (Figure 4). Changes in normalized global warming scores were more modest, ranging from a 834,618 PE saving to a 811,860 PE increase at national scale, while resource depletion savings ranged from 452,534 to 2,185,359 PE (Figure 4).

4 | DISCUSSION

4.1 | Novel findings

Consequential LCA has previously been applied to assess the use of miscanthus as a bioenergy feedstock (Tonini et al., 2012), but never to assess use of miscanthus as a bedding material. We demonstrated the significant environmental consequences associated with the clear but indirect link between the use of miscanthus as a bedding material and the greater availability of straw for use as a bioenergy feedstock. Net environmental outcomes along the extended chain of consequence initiated by the substitution of straw bedding with home-grown miscanthus on livestock farms were shown to be highly dependent on marginal changes in livestock feeding on livestock farms and the type of marginal electricity substituted. GHG emissions and resource depletion were generally reduced when home-grown miscanthus replaced straw bedding as long as displaced grass forage production was not replaced with concentrate feed. The main environmental benefits driven by miscanthus bedding were gained through the diversion of straw to bioelectricity generation and the associated substitution of electricity generated from coal or natural gas. Carbon pricing, wind power (Le & Bhattacharyya, 2011), biomass energy (Welfle, Gilbert, & Thornley, 2014) and solar PVs (Hall & Buckley, 2016) are driving a rapid decline in electricity generation from coal, which could be accelerated by increased availability of straw that can provide replacement baseload generation (Hammond & O'Grady, 2017) through established straw supply chains (Townsend, Sparkes, Ramsden, Glithero, & Wilson, 2018). However, miscanthus bedding production generally increased eutrophication and acidification burdens significantly (Figure 4), and in some cases also increased net GHG emissions, especially if displaced grass forage was compensated for with additional concentrate feed. Many of these important environmental effects of miscanthus bedding would not have been captured by an attributional LCA evaluation.

4.2 | Biomaterials versus livestock production

There is likely to be a proliferation of uses and demands for farmland and biomass currently used to feed livestock as the circular bioeconomy develops (Nattrass et al., 2016). Our study highlights the need to carefully assess implications of new biomass or land uses for livestock production systems which generate considerable pollution, both directly via animal emissions and fertilizer use and indirectly via feed supply chains (Loyon et al., 2016; Mottet et al., 2017). Comparatively small changes in the high pollution loadings, especially nutrient losses, arising from interactions with livestock systems could dramatically change the apparent environmental efficiency of new bio-based products.

Here, we showed that three of four environmental burdens could be increased when miscanthus replaced straw bedding, depending on specific factors, in particular, an increase in the use of concentrate feed to compensate for lost grass forage production, which could drive iLUC emissions through cropland expansion (Styles, Gibbons, Williams, Stichnothe, et al., 2015). However, we also demonstrated that this effect could be somewhat offset by a reduction in animal emissions associated with the accompanying improvement of digestibility of the overall feed ration (Beauchemin, Kreuzer, O'Mara, & McAllister, 2008). There is significant potential to reduce the environmental intensity of extensive cattle and sheep systems (Loyon et al., 2016). Aside from compensatory feeding strategy, factors found to particularly influence environmental outcomes were the quality of the grass displaced by miscanthus, and the effective utilization rates of that grass, in terms of DM intake per hectare by livestock through grazing and silage consumption. Results from the seven livestock farms studied suggest that farmers with good quality (highly digestible) grass and high utilization efficiencies (i.e. high stocking rates) should not convert any of their grassland to miscanthus cultivation for livestock bedding supply, from an environmental perspective, owing to the high risk of pollution 'leakage'. Meanwhile, farmers with lower quality grassland and lower stocking rates are more likely to realize environmental benefits by converting their grassland to miscanthus cultivation. This finding aligns with economic drivers, especially under possible subsidy changes (Downing, Coe, & Uberoi, 2018), and would suggest that if miscanthus bedding becomes popular, its cultivation is likely to become a specialized activity occupying a small proportion of farms within regions dominated by livestock agriculture—such as Wales. One caveat is that miscanthus yields may also be lower for farms with lower stocking densities. More evidence is needed on comparative miscanthus and grass yields across different agro-climatic conditions.

Results of this study indicated market-induced effects of cost-effective miscanthus bedding production and increasing demand for sustainable biomass energy, reflecting policy interactions and consumer behaviour changes (Camia et al., 2018).

4.3 | Mitigation of negative consequences

Pollution 'leakage' via feed displacement could be minimized if the introduction of miscanthus drives improved management of remaining grassland—as shown for D_2 scenarios (Table S9.1). Available data suggest that there is considerable scope for livestock farms to improve both the rates of grass uptake and the digestibility of grasses. The typical ME of grass is 10.5 MJ/kg DM but could be increased to 11–12 MJ/kg DM through variety selection and the timing of grazing, while continuous grazing may only utilize 50% of grass productivity and this could increase to 80% with better management such as rotational grazing (Genever et al., 2016). In this context, the use of bought-in silage is also a potentially sustainable approach to compensate for displaced grass forage production. Such imports are associated with significant upstream burdens from grass production, but avoid the large GHG emission leakage associated with iLUC driven by cropland expansion. Sheep and beef farmers are more likely to buy grass silage than more expensive concentrate feed if feed supplies run low (Genever et al., 2016). Cultivating miscanthus without fertilizer inputs can also reduce net environmental burdens from miscanthus bedding, so long as compensatory concentrate feed is avoided.

4.4 | Prospects for miscanthus being used as a bedding material

Crucially, lack of market has been a major reason cited by livestock farmers for not cultivating miscanthus (Wilson et al., 2014), alongside years of failed energy crop policies (Adams & Lindegaard, 2016). However, the recent demonstration of miscanthus' efficacy as a bedding material (AHDB, 2018; HCCMPW, 2010; Van Weyenberg et al., 2015) paves the way for a new market on the doorstep of livestock farms, where the opportunity costs of cultivating miscanthus are much lower than on arable farms where gross margins per hectare are significantly higher (FBS, 2018). Numerous other factors are likely to favour alternative bedding materials such as miscanthus. The demand for straw as a bio feedstock is projected to increase, along with prices, which will stimulate a search for alternatives among livestock farmers. Simultaneously, the cost of miscanthus establishment, a major deterrent in its cultivation hitherto, is likely to fall significantly following recent advances with seed and plug establishment (Hastings et al., 2017). Nonetheless, government support is still regarded as vital to stimulate adoption (Hastings et al., 2017), and incentive schemes need to be long-term to gain farmer confidence (Thornley & Cooper, 2008). Miscanthus cultivation is a suitable action for agri-environmental support schemes, as its production could provide various ecosystem services including habitat provisioning and soil and water quality benefits at the landscape scale, alongside the climate regulation explored here (Bauen et al., 2010; Holland et al., 2015; Milner et al., 2016; Wynne-Jones, 2013).

Although this study focussed on miscanthus as an alternative bedding material, many other alternative bedding options exist, from other types of home-grown biomass, through mattresses to no bedding (Bruijnis, Hogeveen, & Stassen, 2013; Copeland & Turley, 2008; HCCMPW, 2010). Other biomass crops proposed for use as bioenergy feedstocks in United Kingdom have potential for use as bedding materials, including reed canary grass and willow (Charlton, Elias, Fish, Fowler, & Gallagher, 2009; HCCMPW, 2010; Lord, 2015). Outcomes presented here for miscanthus are likely to approximate to outcomes for other low-input lignocellulosic biomass options such as reed canary grass and short rotation coppice willow (Brandão et al., 2011; HCCMPW, 2010) that can achieve good yields on marginal land (Bauen et al., 2010). Other materials such as woodchips, forest residues, sawdust and shavings could be used for livestock bedding without the need for cultivation on productive farmland, thus reducing the risk of food/feed displacement (HCCMPW, 2010; Smith, Simms, & Aber, 2017). However, the availability of these alternatives will be spatially constrained, and could compete with other uses of residues, including being left in forests to maximize carbon storage (Agostini, Giuntoli, & Boulamanti, 2014). Miscanthus is also very similar to straw, and therefore reduces the risk of handling difficulties and incompatibility with manure management systems that could pose a challenge for more diverse bedding materials (Smith et al., 2017).

4.5 | Limitations of study

In order to quantify farm-level responses to straw diversion, several assumptions were made regarding miscanthus yield potential and farm management options. The yield of home-grown miscanthus is an important determinant in the quantity of grass displaced and overall fertilizer application on farms. One of the advantages of miscanthus cultivation is said to be its low fertilizer requirement (Tonini et al., 2012). However, in this study, fertilized miscanthus required higher rates of fertilizer application than the relatively extensively managed grasslands, at 52 kg N/ha (Defra RB209, 2010; Table S1.1). However, miscanthus may become unresponsive to N application rates greater than 50 kg/ha (Christian, Riche, & Yates, 2008; Lewandowski & Schmidt, 2006), especially when planted on pastures likely to have a high soil N supply (McCalmont et al., 2017). Therefore, the F_1 permutations considered in this study are likely to be worst-case assumptions. On the other hand, there have been mixed reports on the consistency of miscanthus yields (Clifton-Brown, Breuer, & Jones, 2007; Hudiburg, Davis, Parton, & Delucia, 2015; Lewandowski, Clifton-Brown, Scurlock, & Huisman, 2000; Zimmermann, Styles, Hastings, Dauber, & Jones, 2014).

Farmers' attitudes towards miscanthus cultivation and general sustainability will play a key role in the adoption of miscanthus bedding. Farmers may decide to grind miscanthus into finer bedding particles, which would require grinding equipment, and are not considered in this study (Van Weyenberg et al., 2015). Farmers are resourceful and could modify their farm systems in a multitude of ways following the introduction of miscanthus bedding, which may influence environmental outcomes in unpredictable ways (Henriksson, Flysjö, Cederberg, & Swensson, 2011). There are many options to mitigate environmental burdens on beef farms (Nguyen, Doreau, et al., 2013). We could not account for all possible responses to miscanthus bedding integration on livestock farms in this study, but we did mitigate this limitation by covering a range of extremely optimistic to extremely pessimistic possibilities across a large number of scenarios. In doing so, we add to the current literature by highlighting the multiple pathways through which cultivation of new bio feedstocks can influence farm systems.

4.6 | Conclusion

This study demonstrates that the use of miscanthus as an alternative bedding material can support significant GHG mitigation and save fossil resources when the downstream consequence of straw bedding being diverted into bioelectricity generation is accounted for. This outcome means that miscanthus grown for bedding, rather than bioenergy purposes still results in fossil fuel replacement. However, eutrophication and acidification burdens may be increased, along with GHG emissions under worst-case assumptions. Key factors to maximize the environmental sustainability of miscanthus bedding are to ensure effective straw bedding substitution, and to avoid use of concentrate feed to compensate for displaced grass forage production, as well as to minimize fertilization of miscanthus. There is a significant risk of 'carbon leakage' where displacement of grass production by miscanthus cultivation leads to increased demand for concentrate feed to maintain livestock production, potentially driving iLUC emissions via cropland expansion in feed supply chains. Reduced animal emissions associated with improved feed quality only partially mitigate this carbon leakage. This study highlights the need to carefully consider how production of feedstocks for new bio-based products is integrated into farm landscapes in order to avoid exacerbating or displacing large pollution loading from livestock production.

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SUPPORTING INFORMATION

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

How to cite this article: Yesufu J, McCalmont JP, Clifton-Brown JC, et al. Consequential life cycle assessment of miscanthus livestock bedding, diverting straw to bioelectricity generation. *GCB Bioenergy*. 2020;12:39–53. https://doi.org/10.1111/gcbb.12646