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Economic and greenhouse gas costs of *Miscanthus* supply chains in the United Kingdom

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Abstract

Miscanthus has been identified as one of the most promising perennial grasses for renewable energy generation in Europe and the United States [*Mitigation and Adaptation Strategies for Global Change* **9** (2004) 433]. However, the decision to use *Miscanthus* depends to a considerable degree on its economic and environmental performance [*Soil Use and Management* **24** (2008) 235; *Renewable and Sustainable Energy Reviews* **13** (2009) 1230]. This article assessed the spatial distribution of the economic and greenhouse gas (GHG) costs of producing and supplying *Miscanthus* in the UK. The average farm-gate production cost of *Miscanthus* in the UK is estimated to be 40 £ per oven-dried tonne (£ odt^{-1}), and the average GHG emissions from the production of *Miscanthus* are 1.72 kg carbon equivalent per oven-dried tonnes per year (kg CE odt^{-1} yr^{-1}). The production cost of *Miscanthus* varies from 35 to 55 £ odt^{-1} with the lowest production costs in England, Wales and Northern Ireland, and the highest costs in Scotland. Sensitivity analysis shows that yield of *Miscanthus* is the most influential factor in its production cost, with precipitation the most crucial input in determining yield. GHG emissions from the production of *Miscanthus* range from 1.24 to 2.11 kg CE odt^{-1} yr^{-1}. To maximize the GHG benefit, *Miscanthus* should be established preferentially on croplands, though other considerations obviously arise concerning suitability and value of the land for food production.

Keywords: cropland, economic cost, GHG cost, life-cycle analysis, *Miscanthus*, renewable energy

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Introduction

Climate change and energy security are two long-term challenges faced by the UK (DTI, 2007). Under the Climate Change Act 2008, the United Kingdom is committed to an emission reduction target of 80% compared to 1990 levels by 2050. To meet this ambitious target and improve energy security, renewable energy is required as part of the future UK energy portfolio, and the renewable energy share in the United Kingdom by 2020 should be 15% (Clarke *et al*., 2009). Perennial grasses are among the renewable sources considered for generating electricity and heat, because of their potential to reduce greenhouse gas (GHG) emissions relative to fossil fuels, and to serve as carbon sinks by sequestering carbon in soil (McLaughlin & Walsh, 1998; Khanna *et al*., 2008). *Miscanthus* has been identified as one of the most promising perennial grasses for renewable energy generation in Europe and the United States (Heaton *et al*., 2004). However, the decision to use *Miscanthus* depends to a considerable degree on its economic and environmental performance (Richter *et al*., 2008; Smeets *et al*., 2009). It is therefore necessary to assess the production cost and GHG emissions of supply chains of *Miscanthus* in the United Kingdom. Many studies have used life-cycle analysis to separately estimate the production cost (Huisman *et al*., 1997; Bullard & Nixon, 1999; Khanna *et al*., 2008; Smeets *et al*., 2009), and GHG emissions of the supply of *Miscanthus* (St. Clair S *et al*., 2008; Hillier *et al*., 2009; Smeets *et al*., 2009). These studies are closely related to the specified assumptions, and should be integrated to assess the production cost and GHG emissions of the supply of *Miscanthus*, as the production cost and GHG emissions of bioenergy will simultaneously impact the usage of *Miscanthus*. Furthermore, the spatial distribution of the production cost and GHG emissions of *Miscanthus* can be used to optimize the supply strategy for a renewable energy market in the United Kingdom. In this article, we assess the production cost, the transportation cost and GHG emissions of the supply chains of *Miscanthus*, as well as the spatial variation in these costs in the United Kingdom. To understand GHG emissions relative to C-efficient alternatives, GHG emissions are expressed in kilograms of carbon equivalent (kg CE) (Lal, 2004).

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Materials and methods

Miscanthus is a C4 species, which is able to use sunlight and water more effectively than C3 species (Knapp, 1993). It is grown by planting rhizomes of about 10 cm in length. *Miscanthus* yields peak towards the end of autumn, at approximately 13 tonnes per hectare (t ha^{-1}) in the United Kingdom (DEFRA, 2001). The crop is harvested annually so farmers have a regular income and, to some extent, some income security (St. Clair *et al.*, 2008). The harvested crop has low mineral content, which improves its fuel quality (Lewandowski *et al.*, 1995; Lewandowski & Kicherer, 1997).

The production cost and GHG emissions of the supply chains of *Miscanthus* are calculated using life-cycle analysis. The supply chain of *Miscanthus* encompasses establishment to transportation to bioenergy conversion stations where *Miscanthus* is combusted. The management of *Miscanthus* follows 'Planting and Growing *Miscanthus*: Best Practice Guidelines for Application to DEFRA's Energy Crops Scheme' (DEFRA, 2001). In this study we assume no herbicide is applied for *Miscanthus* after the establishment year for weed control (on the basis of the field experiments in Illinois, USA; Khanna *et al.*, 2008). We also assume no application of fertilizer to *Miscanthus*, following St. Clair *et al.* (2008), because *Miscanthus* has a high nutrient-use efficiency. The production cost at farm-gate (£ odt^{-1}) is calculated as:

$$P = \frac{\sum_{t=1}^{T} \frac{C_t}{(1+d)^{t-1}}}{\sum_{t=1}^{T} \frac{Y_t}{(1+d)^{t-1}}}, \qquad (1)$$

where T is the plantation life time, t is year, d is the discount rate and is set to 0.06 (a 6% discount rate was chosen as it is consistent with current farm economic modelling practice; Bauen *et al.*, 2010), Y is yield (odt ha^{-1}) and C is cost (£ ha^{-1}).

The plantation life time for *Miscanthus* is assumed to be 20 years. The calculation of GHG emissions from the production of *Miscanthus* includes all emissions related to field preparation, farming practices undertaken and substances applied (herbicide) when *Miscanthus* is grown until it is harvested (including bailing and loading). Tables 1 and 2 show data collated for production cost and GHG emissions for growing *Miscanthus*.

The transportation of *Miscanthus* can be performed by standard transportation vehicles. Tractors, trucks, trains and ships can be used to transport energy crops (Borjesson & Gustavsson, 1996). The transportation cost and GHG emissions of *Miscanthus* per ton-km depend primarily upon the mode of transportation, and the roundtrip distance to be covered. For transportation distances up to 25 km, tractor-trailer is typically the most cost efficient method (Borjesson & Gustavsson, 1996; Leduc *et al.*, 2009), whereas transportation by truck is the most cost effective option for distances of up to 100 km (Smeets *et al.*, 2009). For more than 100 km, train and ship are the most cost efficient methods (Borjesson & Gustavsson, 1996). We assume that the harvested *Miscanthus* is transported by truck.

Table 2 Greenhouse gas emissions from the production of *Miscanthus*

		Emission (kg CE ha^{-1})	
Operation category	Operation	Year 1	Years 2–20
Establishment*	Broadspectrum herbicide	6.00	
	Ploughing	15.20	
	Potato planter	6.90	
	Heavy roller	64.60	
Postestablishment			
Harvest*	Cutting	10.00	10.00
Storage*	Baling	3.30	3.30

*Lal (2004) and St. Clair *et al.* (2008).

Table 1 Farm-gate production cost for *Miscanthus*

		Cost (£ ha^{-1})			
Cost category	Cost item	Year 1	Year 2–19	Year 20	Source
Establishment	Rhizome costs (20,000 rhizomes ha^{-1})	1300			[a]
	Herbicides (glyphosate)	96			[a]
	Ploughing	48			[b]
	Potato planter	300			[b]
	Heavy roller	38			[b]
Postestablishment	Fixed overheads	87	87	87	[c]
Harvest	Mower conditioner	200	200	200	[c]
Storage	Bales/plastic sheeting	38	38	38	[c]
Plantation removal				100	[c]
Grants	ECS establishment grant	713			[c]

[a]Wales Energy Crops Information Centre. (2011).
[b]Energy Crops Calculator of NNFCC (2011) and Bauen *et al.* (2010).
[c]Bauen *et al.* (2010).
ECS, energy crop scheme.

The transportation cost C (£ odt^{-1}) is expressed as in Bauen *et al.* (2010):

$$C = 4.28 + 0.27d, \tag{2}$$

where d is the distance travelled (km).

Transportation GHG emissions are assumed to be 0.65 kg CE (odt km)$^{-1}$ [derived from Bonilla & Whittaker (2009)].

The yield map of *Miscanthus* in the United Kingdom is derived from Wang *et al.* (2011). It was estimated by the process-based *Miscanthus* model 'Miscanfor', developed by Hastings *et al.* (2009a,b), at a resolution of 1 km^2 for the whole United Kingdom, using mean yield for the period 1975–2002 (Fig. 1). The average dry matter yield of *Miscanthus* was 10.45 odt ha^{-1}.

Results and discussion

The spatial distributions of farm-gate production costs and GHG emissions from the production of *Miscanthus* for the whole United Kingdom are depicted in Figs 2 and 3, respectively. The farm-gate production cost map (Fig. 2) shows that the lowest production costs are spread throughout England, Wales and Northern Ireland, whereas Scotland has the highest production costs. The farm-gate production cost predominantly ranges from 35 to 55 £ odt^{-1}. In Fig. 3, the pattern of GHG emissions from the production of *Miscanthus* is very similar to that of production costs. Greenhouse gas emissions from the production of *Miscanthus* vary from 1.24 to 2.11 kg CE odt^{-1} yr^{-1}. For the average dry matter yield of *Miscanthus* in the United Kingdom of 10.45 odt ha^{-1}, the average farm-gate production cost of *Miscanthus* in the United Kingdom is 40 £ odt^{-1}, and

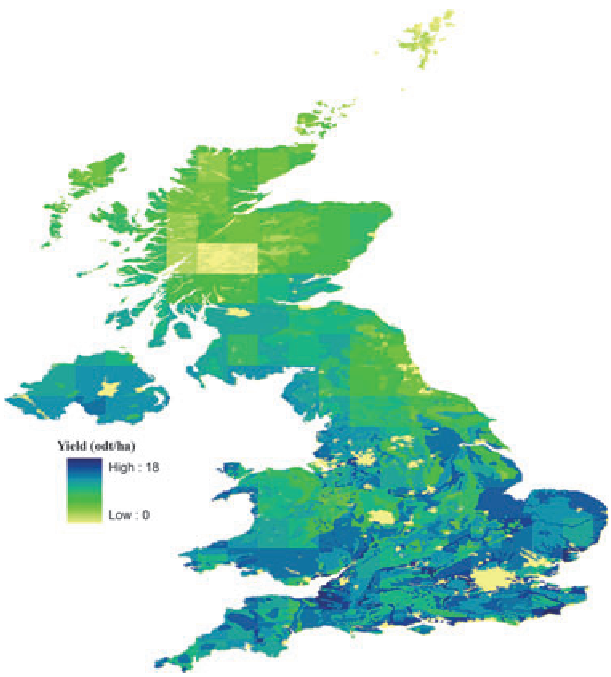

Fig. 1 Yield map of *Miscanthus* in the United Kingdom (Wang *et al.*, 2011).

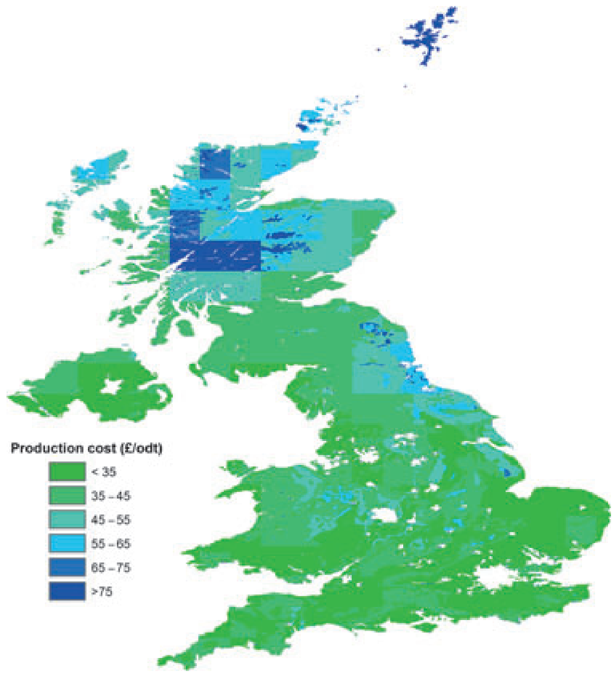

Fig. 2 Farm-gate production costs of *Miscanthus*.

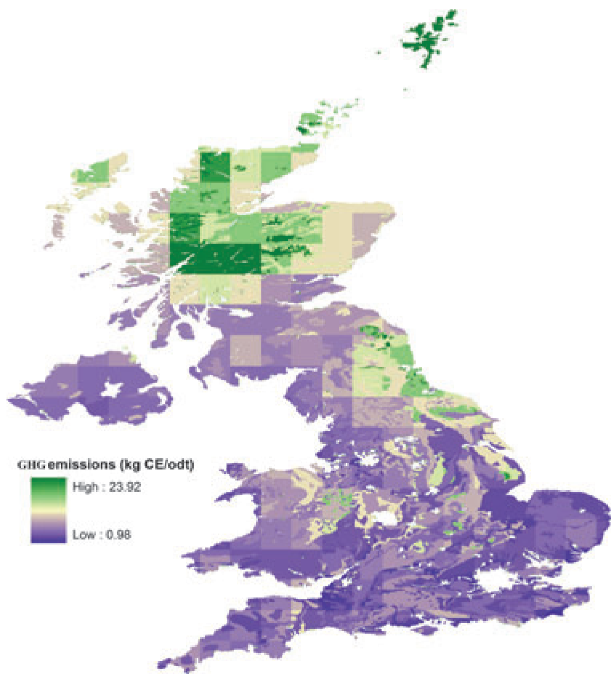

Fig. 3 Greenhouse gas emissions from production of *Miscanthus*.

the average GHG emission from the production of *Miscanthus* is 1.72 kg CE odt^{-1} yr^{-1}. Under the assumption that the average distance travelled to bioenergy stations is 50 km in the United Kingdom, the transportation cost is 17.8 £ odt^{-1} and the transportation GHG emissions are 32.5 kg CE odt^{-1}, respectively. Therefore, the total economic cost of supplying *Miscanthus* to bioenergy stations, which is the sum of farm-gate production cost plus transportation cost, is 58 £ odt^{-1}, and the total GHG emission is 34.22 kg CE odt^{-1}.

The calculated production cost of *Miscanthus* does not include the farm profit. To assess the economic benefit of *Miscanthus*, we translate the production cost into the farm-gate sale price, which considers the farm profit, as the sale price for most energy is easily acquired, rather than the production cost. The average farm-gate sale price, which is the sum of farm-gate production cost plus farm profit, is 46.12 £ odt^{-1}, provided that the farmer profit is 806 £ ha^{-1} (Cambridge & SAC, 2005). This average farm-gate sale price of *Miscanthus* (46.12 £ odt^{-1} or 2.71 £ GJ^{-1}) is attractive compared with the price of gas (4.85 $ per million Btu or 2.81 £ GJ^{-1}) and oil (61.67 $ per barrel or 6.14 £ GJ^{-1}) in 2009, but it is higher than cost of coal (2.05 £ GJ^{-1}) in 2009 (BP, 2010). The total economic cost of supplying *Miscanthus* to bioenergy stations with farmer profit (63.92 £ odt^{-1} or 3.76 £ GJ^{-1}) is less expensive than oil in 2009, but it is more expensive than using gas and coal in 2009.

Miscanthus provides a great GHG benefit compared with fuel oil. When *Miscanthus* is used to displace fuel oil, the saved oil C could be 0.44 t C odt^{-1} (Cannell, 2003). Even if the GHG emissions from the management of *Miscanthus* are considered, the saved oil C is still considerable. Therefore, *Miscanthus* is a more environmentally friendly energy source compared to fuel oil.

The calculated farm-gate production cost of *Miscanthus* will be influenced by farming practices and yields. Different assumptions about agronomic practices for *Miscanthus* will result in different farm-gate production costs. However, rather than analysing the detailed differences among these assumptions, the focus here is to determine the most influential factors on the farm-gate production cost, as the farm-gate production cost of *Miscanthus* contributes 69% of the total economic cost of supplying *Miscanthus* to bioenergy stations, which directly affects the use of *Miscanthus* for energy production. A sensitivity analysis allows us to determine the key variables and possible implications for controlling costs. The sensitivity analysis conducted by Bauen *et al.* (2010) indicated that yield was the most influential cost factor of the farm-gate production cost of *Miscanthus*. Bullard (2001) estimated that a 50% increase in the yield of *Miscanthus* could reduce the per-unit cost by about 25%. Increasing the yield of *Miscanthus* is clearly an effective way of reducing the production cost, which would increase the attractiveness of *Miscanthus* for energy generation.

Richter *et al.* (2008), using a simple model, showed that yields of *Miscanthus* were affected by soil available water capacity, air temperature and precipitation. Tuck *et al.* (2006), using a bioclimatic envelope approach, showed that the best conditions for growing *Miscanthus* were within the temperature range 11–40 °C, and the rainfall range 600–1500 mm yr^{-1}. To determine which factors most influence yield of *Miscanthus*, and thus derive effective policy implications, a sensitivity analysis was performed using the 'Miscanfor' model (Hastings *et al.*, 2009a,b). The analysis was conducted for sites in two major cropland areas in the UK: one in East Anglia and the other in Scotland. Base values are presented in Table 3. Precipitation and solar radiation were shown in the sensitivity analysis to be the most influential factors on yield of *Miscanthus* (Fig. 4). In East Anglia, yield will change by 12% if there is a 10% change in precipitation, and will change by 9% if there is a 10% change in solar radiation. Whereas in Scotland, yield will change by 5% if there is a 10% change in precipitation, and will change by 10% if there is a 10% change in solar radiation. Variations in air temperature have a relatively small influence on yield of *Miscanthus* in both East Anglia and Scotland. As precipitation can be managed through irrigation, yields of *Miscanthus* could be increased by careful irrigation, and the farm-gate production cost of *Miscanthus* could be decreased, though irrigation itself carries an economic and GHG cost. However, it has to be noted that our estimates assume *Miscanthus* with sufficient nutrient supply. On the poor soils, especially in Scotland, it may be necessary to fertilize *Miscanthus* to maintain long-term yields (Christian *et al.*, 2008). Future studies should further examine the influence of nutrient supply on yield of *Miscanthus* and the consequences for GHG emissions.

The calculated production cost of *Miscanthus* will also be influenced by land rent. Land rent has close relation with the land type and the alternative use of the land (i.e. opportunity cost of land). Nix (2008) recommend a base case value of 150 £ ha^{-1} for grade 3 (i.e. good to

Table 3 Base value of parameters of 'Miscanfor' model in sensitivity analysis

	Mean base value	
Parameter	East Anglia	Scotland
Temperature (°C)	10.0	8.5
Precipitation (mm $month^{-1}$)	64	76
Radiation (MJ m^{-2})	8.8	7.9
Cloud (%)	79	80

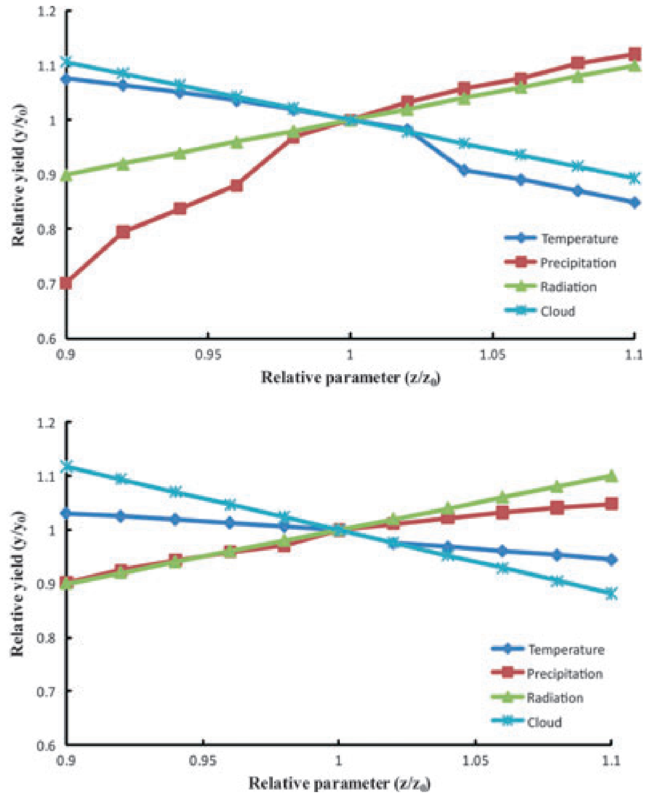

Fig. 4 Sensitivity analysis for *Miscanthus* yield in East Anglia (left) and Scotland (right).

moderate) land in the United Kingdom. Khanna *et al.* (2008) estimated that an increase in the opportunity cost of land by $1 would increase the production cost of *Miscanthus* by $0.05 tonne^{-1}, given the alternative use of land to corn and soybeans. Bauen *et al.* (2010) estimated that the land rent, together with all fixed overheads, cultivation, harvesting and storage costs, could lead to a 10% change in production cost of *Miscanthus*.

The greenhouse gas emissions from the production of *Miscanthus* will be impacted by land use conversion. St. Clair *et al.* (2008) found that conversion from cropland to *Miscanthus* increased soil carbon stocks and reduced GHG emissions relative to the former cropland, whereas conversion of pasture or forest to *Miscanthus* yielded small change to soil carbon, but potential loss of vegetation carbon (in the case of forest conversion). The size of soil carbon emissions shows a strong relationship with the initial soil carbon of the land (Hillier *et al.*, 2009). In Great Britain, the total amount of carbon in the soils is estimated to be 9.8 ± 2.4 billion tonnes (6.9 billion tonnes in Scotland and 2.8 billion tonnes in England and Wales; Dawson & Smith, 2007; Ostle *et al.*, 2009), among which bog habitats contain by far the largest belowground carbon stock (>550 million tonnes) followed by improved grassland (274 ± 25 million tonnes) and arable-horticultural land (198 ± 19 million tonnes) (Ostle *et al.*, 2009). Based upon these previous studies, purely in terms of the carbon/greenhouse gas balance, *Miscanthus* should be established preferentially on croplands, though other considerations obviously arise concerning suitability and value of the land for food production.

The calculated economic cost and GHG emissions of *Miscanthus* are based on information described mainly in UK sources, but will vary with location (fertilizer applied, herbicide applied, soil type, etc.) and farming experience as well as machinery (St. Clair *et al.*, 2008). The sources of uncertainty related with the calculation of GHG emissions of the production of *Miscanthus* have been identified in previous studies (Tan *et al.*, 2002). Given the economic and GHG benefits of *Miscanthus* relative to oil, it is clearly preferable for energy supply, but is still more expensive on average than gas and coal. The transport costs tip the balance in favour of gas compared with *Miscanthus*, so production of energy grasses in close proximity to power stations is likely to be most viable. In some areas, where yield is high, *Miscanthus* is more economically competitive, and it is these areas where *Miscanthus* is the most viable alternative to fossil fuels for energy generation. Our analysis suggests that increasing yield and reducing transport distances will make *Miscanthus* more competitive as a feedstock for energy generation.

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