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Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity

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Abstract

This study uses life-cycle assessment (LCA) to compare greenhouse gas (GHG) emissions from dominant agricultural land uses, and peat and coal electricity generation, with fuel-chains for *Miscanthus* and short-rotation-coppice willow (SRCW) electricity. A simple scenario was used as an example, where 30% of peat and 10% of coal electricity generation was substituted with co-fired *Miscanthus* and SRCW, respectively. *Miscanthus* and SRCW cultivation were assumed to replace sugar-beet, dairy, beef-cattle and sheep systems. GHG emissions of 1938 and 1346 kg CO_2 eq. $ha^{-1}\,a^{-1}$ for *Miscanthus* and SRCW cultivation compared with between 3494 CO_2 eq. $ha^{-1}\,a^{-1}$ for sugar-beet cultivation and 12,068 CO_2 eq. $ha^{-1}\,a^{-1}$ for dairy systems. *Miscanthus* and SRCW fuel chains emitted 0.131 and 0.132 kg CO_2 eq. kWh^{-1} electricity exported, respectively, compared with 1.150 and 0.990 kg CO_2 eq. kWh^{-1} electricity exported for peat and coal fuel chains. 1.48 Mt CO_2 eq. a^{-1} was saved from electricity production, and 0.42 Mt CO_2 eq. a^{-1} was saved from displaced agriculture and soil C-sequestration. The total reduction of 1.9 Mt CO_2 eq. a^{-1} represents 2.8% of Ireland's 2004 GHG emissions, but was calculated to require just 1.7% of agricultural land area and displace just 1.2% of the dairy herd (based on conservative *Miscanthus* and SRCW combustible-yield estimates of 11.7 and 8.81 t $ha^{-1}\,a^{-1}$ dry matter, respectively). A 50% increase in cultivation emissions would still result in electricity being produced with an emission burden over 80% lower than peat and coal electricity. Lower yield assumptions had little impact on total GHG reductions for the scenario, but required substantially greater areas of land. It was concluded that energy-crop utilisation would be an efficient GHG reduction strategy for Ireland.

Keywords: *Miscanthus*; SRC willow; Life-cycle assessment; Ireland; Greenhouse gas emissions; Agriculture

1. Introduction

In 2004, Irish greenhouse gas (GHG) emissions were 25% higher than those of 1990 levels, compared with Ireland's Kyoto Commitment to a maximum GHG emission increase of 13% above 1990 levels during 2008–2012. Livestock production is the dominant agricultural land use in Ireland's maritime climate, resulting in an unusually high agricultural contribution of 28% to national GHG emissions [1]. Grasslands supporting sheep and cattle systems account for 83% of agricultural land area [2], and emit substantial quantities of the potent GHGs methane (CH_4) and nitrous oxide (N_2O), from enteric fermentation and redox conversion of soil-applied nitrogen (N), respectively. Casey and Holden [3] conducted a life-cycle assessment (LCA) on a model farm representative of average Irish dairy farm characteristics. They attributed 49% of annual GHG emissions to enteric fermentation, 21% to fertiliser (production and post-application N_2O emissions), 13% to concentrate feed, 11% to dung management, and 5% to electricity and diesel consumption. There is a rapidly expanding database of international publications containing LCA information pertaining to GHG emissions and energy consumption for different agricultural systems [e.g. 4–11].

As a part of EU Common Agricultural Policy (CAP) reform, from January 2005 Irish farm subsidies changed from being production-indexed to a 'decoupled' system of single-farm payments based on land area farmed during

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2000–2002. Economic modelling of farm-level responses to a continuation of pre-existing policy indicated that livestock numbers would have declined significantly under the baseline scenario (i.e. 12% reduction in dairy cows, 10% reduction in non-dairy cattle, 20% reduction in sheep numbers from 2002 to 2012) [12]. The same modelling predicted that decoupling would lead to further declines in livestock numbers, with an anticipated agricultural GHG emission reduction of $2.8\,\mathrm{Mt\,CO_2\,eq.\,a^{-1}}$ by 2012, relative to 1990 [13]. Economic analysis of *Miscanthus* and short-rotation-coppice willow (SRCW) cultivation indicated that they are likely to be competitive with average gross margins for sugar beet and livestock rearing (with the exception of dairy) [14]. Meanwhile, the promising financial prospects of *Miscanthus* and SRCW wood-chip as fuel for electricity generation via co-firing with peat, and heat production in domestic and commercial boilers, are demonstrated in [15]. Thus, there are good opportunities for energy crops to further displace conventional agricultural production, and utilise destocked land, in Ireland.

Electricity generation in Ireland is particularly GHG intensive, responsible for 22% of Ireland's GHG emissions in 2004 [1], and relying on C-dense coal and indigenous peat to provide approximately 29% and 11%, respectively, of fuel input. Domestic heating and transport emitted similar quantities of GHGs, and all these three sectors have the potential to utilise energy-crop products in place of conventional fossil fuels. Burning biomass is regarded as C-neutral, although the cultivation of energy crops may result in a net emission of GHGs, especially associated with fertiliser production and application, ground preparation and crop harvest, and crop propagation. A number of studies have attempted to quantify these emissions, using LCA-type approaches, for SRCW [e.g. 16–19] and *Miscanthus* [e.g. 20–22]. However, in addition to substituting GHG-emitting fossil fuels, energy-crop cultivation could hasten the displacement of GHG-intensive livestock production, and enhance soil C-sequestration, with further implications for net GHG emission savings.

This paper explores the potential GHG emission reductions that could be achieved in Ireland if some conventional agriculture and electricity production was replaced with energy-crop cultivation and combustion. Specifically, the simple and low-cost route of energy-crop co-combustion in existing peat and coal power stations is explored, following on from work highlighting the potential for co-combustion in Ireland published by van den Broek et al. [23,24] and Sustainable Energy Ireland (SEI) [25]. *Miscanthus* grass (specifically *Miscanthus* x *giganteus)* and SRCW were chosen as promising energy-crop species, based on their high yields [26] and tolerance of wet soils [27], respectively. We consider the production of electricity from these energy crops via co-firing in the three new fluidised-bed-combustion peat power stations operating around the peat bogs of the Midlands (100–150 $\mathrm{MW_e}$) and in the one pulverised coal power station at Moneypoint,[1] on the west coast (915 $\mathrm{MW_e}$). The final aims of this paper are to (i) quantify the life-cycle emissions of electricity generated from co-fired *Miscanthus* and willow; (ii) compare these emissions with the land-uses and fuels energy crops are likely to displace in a simple low-tech co-firing scenario; (iii) assess the magnitude of GHG emissions possible in this particular scenario. Further GHG emission reductions arising from additional utilisation pathways (gasification co-firing and wood-heat), and use of set-aside or destocked grassland, are detailed in [28].

2. Methodology

2.1. Scope, aims and boundaries

In order to construct LCAs for different agricultural systems, it was first necessary to construct an average farm model representative of each system, following the example of [3] for dairy systems. All relevant inputs to the system, and induced processes (e.g. soil N_2O emissions), were then considered in a life-cycle inventory (LCI) up to the point of the farm gate, both for existing agricultural systems and energy-cropping systems. The inventory considered all inputs and processes involving a net emission or sink of the major GHGs (CO_2, CH_4 and N_2O). Published, nationally compiled statistical data were used to define existing agricultural systems, while a synthesis of international literature was used to define SRCW and *Miscanthus* cropping systems. The same process was then applied to electricity-generating systems based on peat, coal and co-fired pulverised wood-chip and chipped *Miscanthus* biomass. All emissions, from the mining of the peat and coal, to ash disposal, were considered in a LCI, and energy-crop cultivation emissions fed into the energy-crop co-combustion LCA. Inventory mass emissions were summed and converted into a final global warming potential measured in CO_2 eq. considered over a 100-year timescale: $CO_2 = 1$, $CH_4 = 23$ and $N_2O = 296$ [29]. Land-use LCAs were calculated and expressed per hectare of land area and per year, over the lifetime of each crop, whilst combustion LCAs were considered per kWh or GJ electricity produced, averaged over the lifetime of the power stations. Electricity emissions were related to land-use emissions according to energy-crop net combustible yield estimates. Although other authors have constructed LCAs for some of these land uses before, this paper draws from a number of studies and applies LCI values from them consistently across all relevant land uses, and to Irish-specific circumstances, to quantify the likely impact of energy-crop cultivation. Upstream, indirect impacts - some of which occur in other countries - were included in the LCAs, but difficult to determine knock-on effects of scenario agricultural production displacement were not (discussed Section 4.5).

[1] Approximately, 20-year remaining lifetime [25] (over 30 years for new peat power stations).

Table 1
Means land areas, fertiliser application rates and livestock numbers for Irish farming systems, as taken from the National Farm Survey 2003 and Fertiliser Use Survey 2000

Land use	Dairy		Cattle		Sheep		Sugar beet
	Area (ha)	N:P:K ($kg\,ha^{-1}\,a^{-1}$)	Area (ha)	N:P:K ($kg\,ha^{-1}\,a^{-1}$)	Area (ha)	N:P:K ($kg\,ha^{-1}\,a^{-1}$)	N:P:K ($kg\,ha^{-1}\,a^{-1}$)
Pasture	23.7	176:12:26	15.9	48:08:17	13.5	48:06:13	
Silage	13.8	151:16:53	6.3	95:14:41	3.1	94:13:39	
Rough grazing	1.5	0	4.1	0	7	0	
Total/average	39.0	160:13:35	26.3	52:08:20	23.6	36:05:11	160:49:165
Livestock	44 milking cows, 58 other cattle		41 cattle		254 sheep		0

2.2. Livestock farming systems

Land management and animal numbers for the farming systems were obtained from the National Farm Survey (NFS) 2003 [30]. These data provide average values for all farms surveyed, according to category (mainly dairy system, mainly cattle system and mainly sheep system). It was necessary to correct these data to ensure that only features integral to the named portion of each system were included in each model farm. Silage area was included for each livestock system (along with calculations for average feed, based on NFS data). Features not integral to each system were removed, and proportionate land areas recalculated (Table 1). Thus, the livestock systems were simplified to ‘dairy’, ‘cattle’ (i.e. beef) and ‘sheep’. Land-use areas and corresponding average fertiliser application rates were taken from the Fertiliser Survey 2000 [31], and are shown in Table 1. The rate of lime application for dairy and beef production was assumed to approximate with the national average application on agricultural land, taken from the National Lime Use survey [32]—resulting in an application rate of $852\,kg\,ha^{-1}$ every 5 years. Milking operations were included in the housing operations of [8], but no further processing or transport of any produce was considered for the land-use LCAs.

2.3. Sugar-beet cultivation

Fertiliser application rates for sugar beet were taken from the Fertiliser Survey 2000 [31]: i.e. 160, 46, and $165\,kg\,ha^{-1}\,a^{-1}$ for N, P and K, respectively (Table 1), and it was assumed that 1 t lime is incorporated every 3 years into sugar-beet soil. Some data specific to sugar beet were taken from Kuesters and Lammel [5] (Table 3), who generated a LCA for sugar-beet systems in Europe. Diesel and lubricating oil consumption during soil preparation were taken from [8]. Harvested sugar beet was stored in barns, construction emissions for which were based on [33], and listed under ‘Housing’ in Table 3. For simplicity, it was assumed that sugar beet was the sole crop on land dedicated to its cultivation (i.e. no crop rotation or catch crops). The inventory cut-off point for the LCA of this system was defined as immediately after storage of harvested sugar beet. No emissions related to transport and processing were considered.

2.4. *Miscanthus* cultivation

The *Miscanthus* rotation used to define the LCA developed here is loosely based on the rotation described by [20], except that plants are propagated using the macro-propagation rhizome division technique recommended in UK Department for Environment, Food and Rural Affairs (DEFRA) best practice guidelines for energy crops [34]. Table 2 outlines the sequence of major activities for *Miscanthus* and SRCW cultivation, as applied to the LCA. The first stage of ground preparation includes herbicide application, at a rate of $2.25\,kg\,ha^{-1}$ of active ingredient [17], followed by subsoiling and ploughing in autumn of year 0. Rhizomes are planted in spring of year 1 using a potato planter, following lifting, rotavation and pick-up using a bulb-harvester of 3-year-old *Miscanthus* rhizomes, where 1 ha supplies rhizomes to plant 10 ha at 20,000 $rhizomes\,ha^{-1}$, at a total energy intensity of $4000\,MJ\,ha^{-1}$ planted [35]. Fertiliser application follows [20], at a rate of 100, 22 and $166\,kg\,ha^{-1}\,a^{-1}$ for N, P and K, respectively, in years of maximum productivity, and it is assumed that 3 t of lime is incorporated prior to planting [35]. Herbicide is applied in the first year after planting, when the emerging crop is vulnerable to competing weeds. Harvest is assumed to occur in late winter of each year (2–15), with winter leaf senescence and storage losses of 30% from annual peak productivity of 20 dry matter (DM) $t\,ha^{-1}\,a^{-1}$ achieved from the fourth year on [36]. During years 2–3, establishing plants were assumed to produce two-thirds of peak productivity, resulting in an average annual yield of $11.7\,t\,ha^{-1}$ delivered for combustion over the 16-year cycle. Harvest was assumed to use 40.25 L diesel per hectare, based on [20]. Annualised construction emissions for baled *Miscanthus* storage barns were taken to be the same as for sugar beet. It was assumed that stored *Miscanthus* bales would have final moisture content of approximately 20% [20]. In the final year, herbicide is applied to new *Miscanthus* growth, and the field ploughed. Stored, baled *Miscanthus* is the final product of the *Miscanthus* land-use LCA.

Table 2
Life-cycle activities for SRCW and *Miscanthus* cultivation

Year	SRCW	Year	*Miscanthus*
0	Herbicide application	0	Herbicide application
	Sub-soiling and ploughing		Sub-soiling and ploughing
1	Herbicide and insecticide (leather jacket control) application	1	Fertiliser application (67, 13 and 67 kg ha^{-1} N, P and K)
	Lime application (3 t ha^{-1})		Lime application (3 t ha^{-1})
	Soil rotovation		Soil rotovation
	Planting using a step or cabbage planter at a density of 15,000 cuttings ha^{-1}		Planting, potato planter at a density of 20,000 rhizomes ha^{-1}
	Rolling		Rolling
2	Coppice		Herbicide application
	Fertiliser application (128, 28 and 178 kg ha^{-1} N, P and K)	2	Fertiliser application (67, 13 and 67 kg ha^{-1} N, P and K)
	Herbicide application		Herbicide application
5	Stick/chip harvest late winter (i.e. winter year 4/5)		Harvest late winter (i.e. winter year 2/3)
			Cut and bale/chop harvest late winter
	Drying[a]		Drying[a]
	Storage on farm		Storage on farm
	Fertiliser application (192, 42 and 267 kg ha^{-1} N, P and K)	3–15	Repeat year 2, but apply fertiliser at 100:20:100 kg ha^{-1} N, P and K from year 4 onwards
8	Late winter harvest (i.e. winter year 7/8)	16	Apply herbicide to new growth and plough
	Drying[a]		
	Storage on farm		
8–22	Repeat year 5–8 rotation 5 more times		
23	Remove stools		

[a]Natural drying.

2.5. SRCW cultivation

Soil preparation for SRCW was assumed to be identical to that for *Miscanthus*, although emissions were divided by the longer rotation assumed for SRCW (7 cuts over 23 years) [37] to generate annualised emissions. Fertiliser application rates were taken from UK DEFRA recommendations [34], and fertiliser was assumed to be applied in the first year of each 3-year rotation (Table 2).

Harvesting was assumed to use 74.85 L diesel, based on [17]. Annualised combustable yields were conservatively estimated at 8.8 DMt ha^{-1} over the 23 years, accounting for two-thirds productivity in the first 3-year cycle, and 15% harvest and storage losses[2] from the 12 DMt ha^{-1} a^{-1} maximum yields [38]. Storage-associated emissions are identical to those for sugar beet and *Miscanthus,* and it was assumed that stored willow bales would have final moisture content of approximately 20% [39].[3] Herbicide application on established SRCW plantations is highly dependent on local circumstances, and in many instances may not be necessary due to rapid canopy closure once the crop is established, and the beneficial effect of some ground cover. Here, it was assumed that worst-case scenario herbicide applications are required every other harvest cycle [40]. In the year following the final harvest, willow re-growth is sprayed with herbicide and the field ploughed over. GHG emissions associated with fencing were based on fence-construction energy requirements given in [33], and were assumed equal for all land uses.

2.6. Land-use inventory data

Energy use was divided into categories of primarily diesel combustion or primarily electricity. For diesel, a lower heating value of 35.9 MJ L^{-1} was used [8], and emissions were calculated based on 1 kg (1.198 L) diesel combustion emitting 3.767 kg CO_2 eq., including indirect emissions [10]. To this were added lubrication oil emissions, calculated at 5% of farm machinery diesel emissions based on [8], and assuming 50% oxidation [41]. For electricity consumption, the national average 2004 GHG-intensity of delivered electricity (0.173 kg CO_2 eq. MJ$_e^{-1}$; [42]) was applied after conversion of primary energy requirement values provided in the literature to delivered electricity, based on an efficiency factor of 0.406 [42]. Indirect emissions associated with agricultural machinery production and maintenance were assumed to be proportionate to fuel consumption following the method of [8]: i.e. 12 MJ L^{-1} indirect energy. Indirect emissions for fertiliser and lime manufacture were taken from representative sources in the literature, after comparison of multiple literature values. For fertiliser, high but all-inclusive

[2]Assume 90% harvest efficiency for above-ground biomass, then 1% per month (for average 6 months) stem DM losses during storage [38].

[3]Gigler et al. [39] observed that outdoor storage of baled willow harvest enabled natural drying of the wood, from harvested moisture contents of around 50%, down to below 15%. A 20% moisture content is used as a realistic condition for naturally dried willow-bales in the LCA.

manufacturing, packaging and transport energy intensities of 79.6, 34.5 and 10.5 MJ kg^{-1} for N, P and K, respectively [17], were used, to which were added manufacturing N_2O emissions of 9.63 g kg^{-1} N. For lime, combined manufacture and calcification emissions quoted by [17] were divided into manufacturing and soil emissions based on the energy requirement of 6.43 MJ kg^{-1}. Soil emissions following fertiliser or manure application and grazing, and direct animal emissions, were based on values used in the NIR [1]. Animal waste storage emissions were grouped with soil emissions for classification purposes. Table 3 lists the emission factors applied to the main activities and processes accounted for in the LCA. The multiplication factors displayed were used to arrive at annual GHG emissions per hectare for each inventory item and for each land-use system, based on the proportional temporal and spatial occurrence of each activity over a whole rotation for each land-use system. It was assumed that soil C remained constant after conversion of grassland to energy cropping (discussed later), but increased by 0.513 and 1.163 t ha^{-1} a^{-1} after conversion of arable land to SRCW and *Miscanthus* cultivation, respectively [43].

2.7. Peat and coal combustion

Direct CO_2 emissions from peat and coal combustion in power stations for the reference scenarios were based on the SEI co-firing report [25]. From this report, coal and peat annual generating capacities were calculated at 23.7 and 9.18 PJ a^{-1} exportable electricity, respectively. Indirect

Table 3
GHG emissions for operations undertaken for the land uses compared in this study, expressed in ha^{-1} L^{-1} diesel use or per kg active ingredient

Operation	Unit	GWP	Dairy	Cattle	Sheep	Sugar beet	*Misc.*	SRCW
Direct emissions								
Soil preparation								
Sub-soiling	CO_2 eq. ha^{-1}	83.38 [8]	0	0	0	0	0.063	0.044
Ploughing[a]	CO_2 eq. ha^{-1}	83.38 [8]	0	0	0	1	0.125	0.087
Cultivating	CO_2 eq. ha^{-1}	43.50 [8]	0	0	0	1	0.063	0.044
Rolling	CO_2 eq. ha^{-1}	6.59 [8]	0	0	0	1	0.063	0.044
Planting	CO_2 eq. ha^{-1}	115.4 [20]	0	0	0	0	0.063	0.044
Sowing	CO_2 eq. ha^{-1}	10.88 [8]	0	0	0	1	0	0
Maintainance								
Fertiliser spreading	CO_2 eq. ha^{-1}	6.59 [8]	2	2	1.50	2	1.875	0.608
Lime application	CO_2 eq. ha^{-1}	26.36 [8]	0.20	0.20	0.20	0.53	0.063	0.043
Slurry spreading	CO_2 eq. ha^{-1}	72.27 [64]	1	1	0	0	0	0
Pesticide application1	CO_2 eq. ha^{-1}	4.94 [8]	0	0	0	3.00	0.188	0.304
Housing operations (dairy)	CO_2 eq. ha^{-1}	817.2 [8]	1	0.14	0.04	0	0	0
Harvest								
Cutting + baling	CO_2 eq. ha^{-1}	246.6 [33,20]	0.18	0.12	0.06	0	0.537	0.304
Lifting	CO_2 eq. ha^{-1}	61.63 [8]	0	0	0	1	0	0
Indirect emissions								
Propagation (Misc.)	CO_2 eq. ha^{-1}	288.74 [35]	0	0	0	0	0.063	0.007
Seed	CO_2 eq. ha^{-1}	11.81 [5]	0	0	0	1	0	0
Machinery	CO_2 eq. L^{-1}	0.90 [8]	*	*	*	*	*	*
Fencing-border	CO_2 eq. ha^{-1}	776.48 [33]	0.04	0.04	0.04	0.04	0.040	0.040
Fencing-internal	CO_2 eq. ha^{-1}	869.69 [33]	0.07	0.07	0.07	0.07	0.067	0.067
Fuel	CO_2 eq. L^{-1}	0.53 [8]	*	*	*	*	*	*
Lubricating oil	CO_2 eq. L^{-1}	0.19 [8]	*	*	*	*	*	*
Fertiliser N	CO_2 eq. kg^{-1}	8.63 [33]	160	52	36	160	94	58
Fertiliser P	CO_2 eq. kg^{-1}	2.57 [33]	13	8	5	46	19	13
Fertiliser K	CO_2 eq. kg^{-1}	0.79 [33]	35	20	11	165	94	81
Lime	CO_2 eq. kg^{-1}	1.10 [9]	170	170	170	333	188	130
Pesticide	CO_2 eq. kg^{-1}	6.3 [9]	0	0	0	6.75	0.422	0.685
Feed concentrate	CO_2 eq. kg^{-1}	1.16 [3]	1585	932	139	0	0	0
Housing (dairy)	CO_2 eq. ha^{-1}	356.3 [8,33]	1.000	0.424	0.120	0.172	0.172	0.172
Animal and soil emissions								
Fertiliser N_2O	CO_2 eq. kg^{-1} N	5.58 [1]	160	88	36	160	100	64
Slurry N_2O	CO_2 eq. kg^{-1} N	4.83 [1]	70	27	0	0	0	0
Grazing N_2O (dairy)	CO_2 eq. ha^{-1}	1059 [1]	1	0.37	0.63	0.00	0	0
Enteric fermentation	CO_2 eq. ha^{-1}	4305 [1]	1	0.41	0.46	0.00	0	0

Numbers under the land-use columns indicate the multiplication factor necessary to give CO_2 eq. ha^{-1} a^{-1} for a full rotation of each land-use system.
[a]Ploughing includes root removal in the final year.

extraction, mining and transport emissions associated with peat and coal electricity chains were taken from [44], and the contributions of CH_4 and N_2O to combustion emissions were taken from [1] for peat and coal electricity production. Connolly and Rooney [44] produced a detailed LCA for the environmental impact of peat and coal electricity generation based on the Edenderry and Moneypoint power stations, from mining and peat extraction to final ash disposal, but did not include construction-related GHG emissions. Coal is sourced from the USA and Colombia, and transported via train and ship to Moneypoint. The greatest uncertainty in the peat combustion LCA is associated with the impact of peat extraction on peat bog emissions, estimated to be a net increase in peat bog emissions of $2908\,kg\,CO_2\,eq.\,ha^{-1}\,a^{-1}$ after drainage (the balance of increased C oxidation set against reduced CH_4 and N_2O emissions, based on data presented by [44]). For all fuel combustion, indirect construction and decommissioning GHG emissions were calculated per GJ electricity produced, based on [45]. They assumed emissions of approximately $1.6\,kg\,CO_2\,eq.\,GJ^{-1}$ electricity produced from both coal, and co-fired straw and wood, in a $509\,MW_e$ pulverised coal power plant in Germany. Table 4 summarises the major inputs to the combustion LCAs.

2.8. *Miscanthus* and SRC combustion

It is assumed that late harvesting and some natural air-drying during covered storage for bundled willow result in modest final SRCW and *Miscanthus* moisture contents of approximately 20% wet weight [17,22,39]. Although this paper does not examine spatial distribution of energy cropping potential in detail, it is assumed that SRCW is more appropriate in the wetter west, where most grassland agriculture occurs, and *Miscanthus* cultivation is better suited to drier areas of the SE and Midlands, where most tillage agriculture occurs. Thus, an indicative scenario is developed where SRCW wood-chip supplies 10% fuel-energy input to Moneypoint coal power station in County Clare, and *Miscanthus* supplies 30% fuel-energy input to the three peat power stations in the Midlands (Table 4), based on [25]. In all cases, an average transport distance of 50 km is applied.

Prior to combustion with peat, *Miscanthus* must be chopped, whilst willow wood must be chipped and pulverised for injection into the pulverised coal boilers at Moneypoint. Van Loo and Koppejan [46] attribute an energy consumption of $0.054\,GJ\,t^{-1}$ DM for wood chipping. It is assumed here that the same quantity of energy is required for *Miscanthus* chopping, and a further $0.144\,GJ\,t^{-1}$ DM is required for chipped willow wood pulverisation [46]. For simplicity, it is considered that chipping/chopping is powered by diesel, whilst pulverisation at Moneypoint is powered by electricity. *Miscanthus* and willow wood contain a lower proportion of N than coal or peat, and have been found to reduce N_2O emissions from co-fired coal combustion [46]. However, N_2O emissions vary widely according to the specific technology used and operating conditions applied. Therefore, it was conservatively assumed that combustion N_2O (and minor CH_4) emissions from *Miscanthus* and willow combustion were the same as for peat. Biomass co-firing has no effect on net electrical-conversion efficiency in the peat power stations, and results in a negligible reduction in the net efficiency of the Moneypoint power station (boiler efficiency decreases from 93.4% to 93.3% due to higher moisture content in biomass compared with coal [25]). Therefore, peat and coal net energy content to electricity conversion efficiencies of 38.4% and 37.5% were applied to co-fired *Miscanthus* and SRCW electricity generation, respectively.

2.9. Sensitivity analyses

Sensitivity analyses were performed by changing those parameters with the least certainty attached to their values. The distance over which crops were transported for combustion was tested for impact on the LCA, with variation between 30 and 100 km. Both cultivation emissions per ha and yield were altered, by $\pm 50\%$. In the case of yield, cultivation emissions per hectare were corrected to account for harvest fuel consumption and fertiliser application rates changed in direct proportion to yield changes. Yield changes were also translated into changed land-area requirements for each GJ electricity produced from energy crops.

Table 4
Major inputs into combustion LCAs for the four fuels considered

	Peat	Coal	*Misc.*	SRCW
Moisture content (% weight)	55 [44]	10 [44]	20 [22]	20 [39]
Energy content ($GJ\,t^{-1}$)	7.7 [44]	28.04 [44]	14.46 [65]	14.46 [65]
Prep/extraction ($kg\,CO_2\,eq.\,t^{-1}$)	328 [44]	26.52 [44]	332 [46]	12.16 [46]
Combustion ($kg\,CO_2\,eq.\,t^{-1}$)	900 [1]	2680 [1]	203	193
Transport ($kg\,CO_2\,eq.\,t^{-1}$)	0.48 [44]	47.86 [44]	4.24 [17]	4.24 [17]
Scenario quantity ('wet'tonnes a^{-1})	2,173,295	2,028,531	498,048	438,889
Area required (ha)	–	–	34,055	39,899

Preparation and extraction emissions account for chipping/pulverisation and mining. Values are for 'wet' weight tonnes.

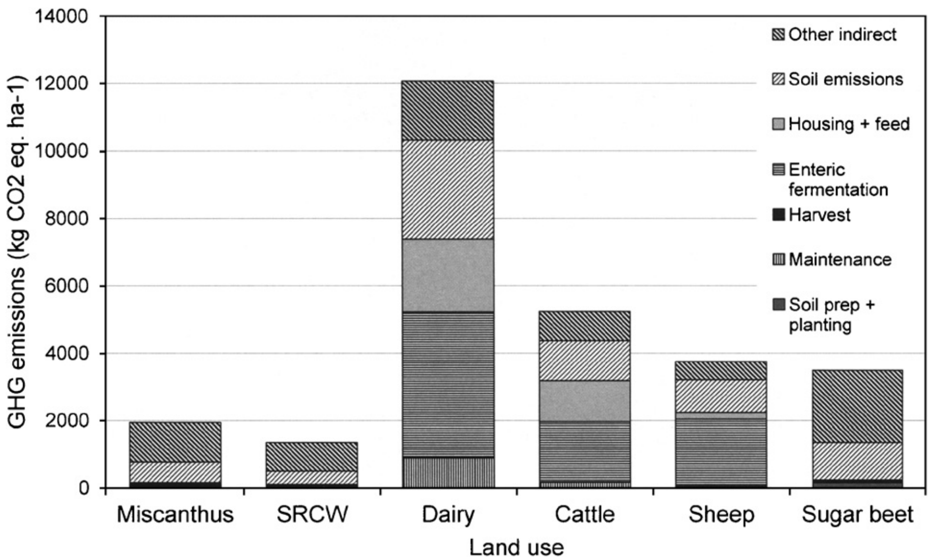

Fig. 1. GHG emissions per ha per year, classified by origin, calculated from the LCAs for *Miscanthus* and SRCW cultivation compared with reference land uses.

3. Results

3.1. Land-use GHG emissions

When annualised over the rotation lifetimes of *Miscanthus* (16 years) and SRCW (23 years), GHG emissions arising from energy-crop cultivation are low compared with conventional agricultural land uses (Fig. 1). *Miscanthus* cultivation is responsible for an annual average emission of 1938 kg CO_2 eq. ha^{-1}, while SRCW cultivation is responsible for an annual average emission of 1346 kg CO_2 eq. ha^{-1}. This compares with annual GHG emissions of 12,068 kg CO_2 eq. ha^{-1} calculated for dairy systems. Cattle, sheep and sugar-beet cultivation are associated with intermediate GHG emission intensities, though even the least GHG-intensive conventional land use, sugar-beet cultivation, is associated with GHG emissions 50% higher than for *Miscanthus*. Fig. 1 also shows a breakdown of GHG emissions into source categories. Enteric fermentation of CH_4 contributes substantially to all the livestock system emissions (e.g. accounting for 36% of dairy emissions), while soil emissions are substantial across all land uses, dominated by fertiliser and animal waste-application-induced N_2O emissions, and including lime calcification emissions. For the livestock systems, waste-storage emissions were classified under soil emissions, though made relatively small contributions (e.g. 18% of dairy soil emissions). Housing operations contribute to relatively high 'maintenance' emissions for dairy land use, while maintenance and soil preparation and planting emissions are low for the other land uses. Over the cultivation cycle, the largest source of direct emissions from energy-crop cultivation is harvest fuel consumption.

Indirect emissions were substantial for all land uses, and in all instances are dominated by N-fertiliser manufacture, which accounts for between 30% (cattle) and 65% (*Miscanthus*) of indirect emissions. When soil emissions arising from fertiliser-N application are also considered, fertiliser application contributes heavily to overall emissions, especially for non-livestock systems. For example, the manufacture, packaging and transport of the 87.5 kg of average[4] annual fertiliser-N required for 1 ha of *Miscanthus* cultivation requires 6965 MJ of primary energy, associated with fossil-fuel emissions of 755 kg CO_2 eq.,[5] while the application of this fertiliser results in soil emissions of 1.89 kg N_2O (558 kg CO_2 eq.) — thus, contributing 1313 kg ha^{-1} (68%) to the 1938 kg ha^{-1} total annual CO_2 eq. emitted by *Miscanthus* cultivation. Indirect emissions for livestock land uses were also divided into components attributable to housing and concentrate feed production in Fig. 1, and it is apparent that these activities account for a substantial proportion of overall dairy and cattle emissions.

3.2. Fuel processing and combustion emissions

Over the entire fuel chain, co-fired *Miscanthus* and SRCW emit almost identical quantities of CO_2 eq. kWh^{-1} net electricity generated — 0.131 and 0.132 kg, respectively. This compares with 1.150 and 0.990 kg CO_2 eq. kWh^{-1} net electricity for milled peat and pulverised coal combustion, respectively. Fig. 2 shows a breakdown of these emissions, and highlights that energy-crop emissions are primarily attributable to cultivation (accounting for 67% and 62% of emissions from *Miscanthus* and SRCW electricity production, respectively). Transport of the fuel to the power

[4]Averaged over the plantation lifetime—less than the 100 kg ha^{-1} a^{-1} applied during max yield years.

[5]Energy supplied by combination of gas, electricity and oil-applied intermediate oil emission factors in this study.

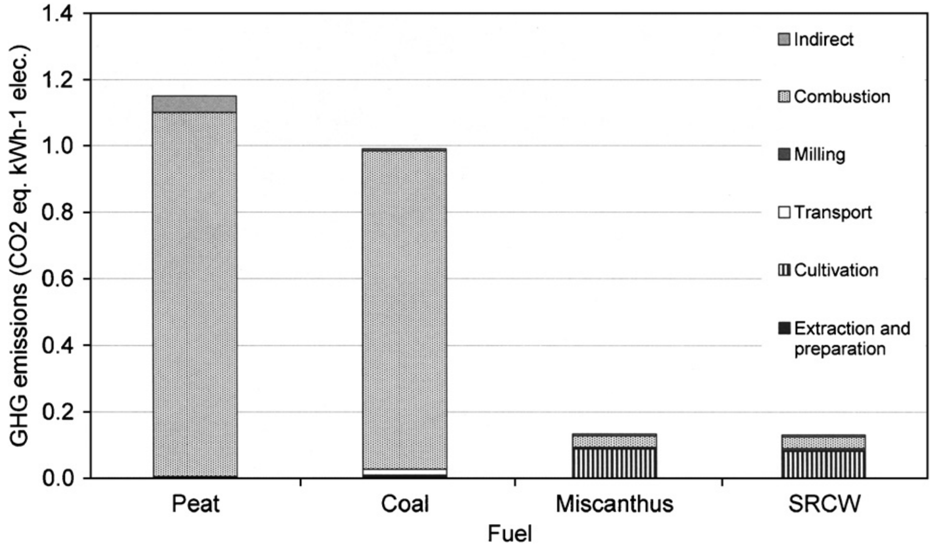

Fig. 2. GHG emissions over the entire fuel chain for electricity production from peat and coal compared with peat-co-fired chipped *Miscanthus* and coal-co-fired milled willow (kWh^{-1} exported electricity).

station is responsible for only a very small proportion of total GHG emissions, even in the case of long-distance coal transport. Milling (chopping *Miscanthus* and chipping followed by pulverisation for SRCW) emissions are also minor, with most of the remaining energy-crop electricity emissions (~25% of total) attributable to combustion release of N_2O and CH_4. Combustion emissions, primarily CO_2, dominate peat and coal electricity GHG burdens (contributing approximately 95% and 97%, respectively). Indirect emissions, mainly arising from construction and decommissioning, were relatively minor when considered over the remaining plant lifetimes. Higher indirect emissions for peat combustion reflect the inclusion of emissions arising from peatland drainage for harvesting (calculated at approximately 0.044 kg CO_2 eq. kWh^{-1} electricity).

3.3. Combined GHG emission reduction

Table 5 displays net GHG emission reductions arising when both land use and electricity substitutions are considered. To do this, emission savings from displaced peat and coal are based on net energy-crop electricity emissions, minus cultivation emissions, which are accounted for at the land-use stage of the fuel chain. When displaced agricultural emissions are considered as part of the fuel chain, reductions in GHG emissions per GJ electricity produced, and total emission reductions, increase. On an area basis, total annual GHG emission reductions range from 18,028 kg CO_2 eq. $ha^{-1}\,a^{-1}$ for SRCW co-fired with coal and replacing sheep farming to 35,209 kg CO_2 eq. for *Miscanthus* co-fired with peat and replacing dairy agriculture (Table 5). When long-term (100 years) soil C accumulation rates under *Miscanthus* and SRCW planted on tillage land are taken into consideration [43], net GHG emission reductions arising from the displacement of sugar beet with *Miscanthus* and SRCW were greater than reductions resulting from the displacement of grassland cattle or sheep systems (Table 5). Emission reductions arising from the displacement of conventional agricultural systems were substantial. In the instance of SRCW co-fired with coal and displacing dairy agriculture, displaced diary emissions of 10,722 kg CO_2 eq. $ha^{-1}\,a^{-1}$ equated to 70% of the emission reduction arising from coal electricity displacement (15,623 kg CO_2 eq. $ha^{-1}\,a^{-1}$), and 40% of the combined land-use/electricity-generation emission reduction (Table 5).

To explore potential impacts of these GHG emission reductions on a national basis, a simple scenario of 30% peat and 10% coal electricity substitution with co-fired *Miscanthus* and SRCW, respectively, was considered (Table 4). The 34,055 ha of *Miscanthus* cultivation was assumed to displace sugar beet, and the 39,899 ha of SRCW cultivation was assumed to displace equal areas of dairy, beef and sheep agriculture. The key inputs to this scenario are highlighted in bold in Table 5, and amount to an annual national GHG emission reduction of 1.90 Mt CO_2 eq. (2.8% total national emissions in 2004), of which 1.48 Mt is attributable to peat and coal displacement, and 0.42 Mt to land-use displacement. The total land area required, 73,954 ha, represents just 1.7% of the 4,305,000 ha appropriated for agricultural use in Ireland in 2004 [2]. Sensitivity analyses presented in Table 6 indicate that GHG emission reductions per hectare are heavily dependent on yield, with a 50% yield increase resulting in an annual GHG emission reduction of 44,814 kg CO_2 eq. $ha^{-1}\,a^{-1}$ for *Miscanthus* (compared with 30,901 kg CO_2 eq. $ha^{-1}\,a^{-1}$ for sugar-beet displacement in the standard scenario: Table 5). However, changes in GHG emission savings are proportionately lower than yield changes as a result of the assumption that certain cultivation emissions (i.e. those attributable to fertiliser application, harvest and storage) will vary in accordance

Table 5
Total annual GHG reductions per ha of land and per GJ electricity produced, considering both land-use and fuel substitution by *Miscanthus* and SRC willow

Energy crop	Fuel replaced	Ag. replaced	Elec. Prod. ($GJ_e\,ha^{-1}\,a^{-1}$)	Soil CO_2 seq. ($kg\,CO_2\,eq.\,ha^{-1}\,a^{-1}$)	Elec. GHG red.[a] ($kg\,CO_2\,eq.\,ha^{-1}\,a^{-1}$)	Ag. GHG red. ($kg\,CO_2\,eq.\,ha^{-1}\,a^{-1}$)	Total CO_2 eq. red.	
							($ha^{-1}\,a^{-1}$)	(GJ_e^{-1})
Miscanthus	**Peat**	Dairy	81.5	0.00	25,080	10,130	35,209	432
		Cattle	81.5	0.00	25,080	3,299	28,378	348
		Sheep	81.5	0.00	25,080	1,813	26,893	330
		Sugar beet	**81.5**	**4265**	**25,080**	**5,821**	**30,901**	**379**
	Coal	Dairy	81.5	0.00	21,438	10,130	31,568	387
		Cattle	81.5	0.00	21,438	3,299	24,737	303
		Sheep	81.5	0.00	21,438	1,813	23,251	285
		Sugar beet	81.5	4265	21,438	5,821	27,259	334
SRCW	Peat	Dairy	59.9	0.00	18,297	10,722	29,019	485
		Cattle	59.9	0.00	18,297	3,891	22,188	371
		Sheep	59.9	0.00	18,297	2,405	20,702	346
		Sugar beet	59.9	1881	18,297	4,030	22,327	373
	Coal	**Dairy**	**59.9**	**0.00**	**15,623**	**10,722**	**26,345**	**440**
		Cattle	**59.9**	**0.00**	**15,623**	**3,891**	**19,614**	**326**
		Sheep	**59.9**	**0.00**	**15,623**	**2,405**	**18,028**	**301**
		Sugar beet	59.9	1881	15,623	4,030	19,653	328

Bold-highlighted rows represent components of indicative scenario.
[a]Based on net electric emissions (LCA emissions minus the cultivation emissions accounted for under agricultural land-use emissions).

with yields. For example, under the 50% yield reduction scenario, annual cultivation emissions are reduced from 1938 and 1346 to 1169 and 839 $kg\,CO_2\,eq.\,ha^{-1}$ for *Miscanthus* and SRCW, respectively (Table 6). Net GHG emission savings per hectare were relatively insensitive to changed cultivation emissions. A 50% increase in cultivation emissions resulted in 6% and 7% lower area-based GHG emission reduction for *Miscanthus* and SRCW, respectively.

Emissions per GJ electricity produced were most sensitive to cultivation emissions, more than doubling in response to a change in cultivation emissions from 50% below to 50% above the standard value (i.e. a tripling in cultivation emissions) calculated in the LCA (Table 6). Although lower yields resulted in significantly lower area-based GHG emission reductions, greater total emission reductions for the lower yield estimates reflect the greater area of displaced agricultural land-use and the lower emissions per hectare in the low yield scenarios. The land area required for a 50% yield reduction is, proportionately, three times that required for a 50% yield increase, and the displaced agricultural emissions more than compensate for the modest increases in electricity-production emissions (by 6.64 and 7.40 $kg\,CO_2\,eq.\,GJ^{-1}$ electricity for *Miscanthus* and SRCW, respectively) under the lower yielding compared with the higher yielding scenarios. Varying transport distances had a minor effect on area based and overall GHG emission reductions from energy crops.

4. Discussion

4.1. Cultivation emissions

Land-use GHG emissions originate from a diversity of sources, some of which are better understood and more reliably quantified than others. GHG emissions arising from field operations and machinery use are well summarised from the literature, modelled and validated in [8]. These emissions were calculated to be minor in the context of the LCAs for energy cropping and conventional agricultural systems studied here. A major source of emissions was fertiliser-N, through both its manufacture and post-application soil-N_2O emissions. Fertiliser application rates for conventional agricultural systems, taken from the Fertiliser Survey 2000 [31], should be relatively accurate. Fertiliser application rates of 100 and 75 $kg\,ha^{-1}\,a^{-1}$ for *Miscanthus* and SRCW [20,34] may err on the high side. Both [22] and [47] suggest a replenishment N-application rate of 50 $kg\,ha^{-1}\,a^{-1}$. The use of this N-application rate in the LCA would have decreased annual *Miscanthus* cultivation emissions by 31% (within the $\pm$ boundaries considered by the sensitivity analyses).

Although not constituting a particularly large contribution to annualised GHG emissions here (only 20 $kg\,CO_2\,eq.\,ha^{-1}$), *Miscanthus* propagation has previously been considered as an energy and GHG-intensive stage of initial crop establishment. Lewandowski et al. [20]

Table 6
Effect of varying yield, cultivation emissions and transport distance on GHC emissions/emission reductions in the national co-firing scenario outlined in Section 3.3, expressed on an area and national basis, and per GJ electricity produced

Yield (DM t ha^{-1} a^{-1})	Cult. emis. (kg CO_2 eq ha^{-1} a^{-1})	Transport dist. (km)	Gross[a] elec. emis. (kg CO_2 eq. GJ^{-1})	Net[b] elec. emis. (kg CO_2 eq. GJ^{-1})	Area (ha)	Elec. GHG red. (t CO_2 eq. a^{-1})[c]	Total GHG red. (t CO_2 eq. a^{-1})	Area GHG red. (kg CO_2 eq. ha^{-1} a^{-1})
Miscanthus								
−50%	1169	50	40.82	12.12	67,568	847,294	1,148,472	16,997
+50%	2697	50	34.18	12.12	22,523	847,294	1,009,344	44,814
11.7	−50%	50	24.44	12.12	34,055	847,294	1,078,530	31,870
11.7	+50%	50	49.07	12.12	34,055	847,294	1,012,522	29,931
11.7	1938	30	36.51	11.82	34,055	848,130	1,046,361	30,925
11.7	1938	100	37.52	12.88	34,055	845,206	1,043,438	30,839
SRCW								
−50%	839	50	42.19	14.16	79,175	618,465	1,107,723	13,991
+50%	1852	50	34.79	14.16	26,392	618,465	754,809	28,600
8.8	−50%	50	25.40	14.16	39,899	618,465	898,503	22,519
8.8	+50%	50	47.88	14.16	39,899	618,465	817,956	20,501
8.8	1346	30	36.33	13.85	39,899	619,206	845,546	21,192
8.8	1346	100	37.42	14.94	39,899	616,612	842,952	21,127

[a]Gross emissions are total LCA emissions, including cultivation emissions also accounted for under agricultural land-use change.
[b]Net emissions are total LCA emissions minus cultivation emissions accounted for under agricultural land-use change.
[c]Based on the net electricity emissions.

attributed 45,000 MJ ha^{-1} to the micro (*in vitro*)-propagation of *Miscanthus* plantlets, mainly due to heating-oil emissions arising from greenhouse over-wintering of plantlets. However, both [34] and [48] recommend macro (rhizome) propagation due to superior establishment rate and reduced costs compared with micro-propagation. Rhizome propagation is estimated to require just 4000 MJ ha^{-1} in machinery diesel and energy for chilling stored rhizomes [35]. This highlights the ongoing development of energy-crop cultivation, with probable future improvements in both their GHG balance and cost-effectiveness. As with propagation emissions, significant fence and storage-barn construction emissions made relatively small contributions (approximately 150 kg CO_2 eq. ha^{-1}) to the annualised LCA when their 25-year life-spans were considered.

4.2. Soil emissions

The most uncertain aspects of the LCA are those relating to soil processes and emissions. Here, simple fractions of applied N were assumed to be emitted directly from soils as N_2O, consistent with national GHG accounting procedures [1] and based on IPCC emission inventory guideline default values [29]. These emission factors account for N losses via ammonia volatitilisation, different types of animal wastes and different means of storage. Calculated N_2O emissions of 1.9 and 1.2 kg ha^{-1} a^{-1} for *Miscanthus* and SRCW in this paper are within the range quoted by Heller et al. [37], who attributed 1.71 kg N_2O ha^{-1} a^{-1} to SRCW cultivation, and by Hanegraaf et al. [21], who suggest emission factors of 1.1 and 1.2 kg ha^{-1} a^{-1} for *Miscanthus* and SRCW (*including* combustion emissions). However, the emission factor of 0.0125 for fertiliser applied N used here compares with an equivalent emission factor of 0.034 calculated for intensively managed Irish grasslands, based on field-scale N_2O flux measurements [49]. Although fertiliser application rate has been found to be a major driver of N_2O emissions [10,50–52], factors such as crop type [10,53], the type of fertiliser applied [50], soil type [10,54] and climate [53,54] will also affect emissions. Changes in N_2O emissions arising from energy-crop cultivation could therefore be highly site-specific. Work is needed to quantify N_2O fluxes over *Miscanthus* and willow stands in Irish conditions.

A number of studies have observed a rapid increase in organic matter mineralisation after grass or legume cover crops have been incorporated into the soil, increasing both CO_2 and N_2O emissions [10,55,56]. However, there is evidence that the long rotation and extensive fine-root system of SRCW, and the below ground rhizome mass of *Miscanthus*, contribute to long-term below ground C storage equal to or greater than under grassland systems [18,55,57]. Matthews and Grogan [43] used long-term soil C data and C-cycle modelling to predict soil C accumulation rates of 0.513 and 1.16 t C ha^{-1} a^{-1} over 100 years for SRCW and *Miscanthus*, respectively, planted on previously tilled soils. These values were used to account for soil C accumulation where energy crops replace sugar beet in this study, but do not consider the one-off increases in *Miscanthus* rhizome C storage (estimated at 15.6 t C ha^{-1} [43]), root C (11 t C ha^{-1} for *Miscanthus* [43]) or above ground biomass C storage increases. Soil C accumulation rates will be dependent on existing soil C content, soil structure and conditions reflective of climate (e.g. moisture content and temperature). Therefore, as with N_2O emissions, soil C accumulation rates are likely to be site-specific. Nonetheless, soil C accumulation represents one of the numerous environmental advantages of *Miscanthus* and SRCW compared with traditional annual energy-crops such as sugar beet and rapeseed.

4.3. Electricity production GHG emissions

Data presented here indicate the possibility to displace significant quantities of GHG emissions from peat and coal electricity generation through simple, low-tech substitution of these fuels with energy crops in Ireland. In this study, peat and coal electricity production were calculated to emit 1.150 and 0.990 kg CO_2 eq. kWh^{-1} net electricity exported. When all cultivation emissions were accounted for, co-firing substitution of peat with chopped *Miscanthus* and coal with pulverised willow wood was found to reduce these GHG emissions by approximately 89% and 87%, respectively (not accounting for GHG emission reductions arising from land-use displacement). It was conservatively assumed that direct combustion emissions of CH_4 and N_2O were similar for energy crops as for peat. In practice, these emissions should be lower due to lower N contents in *Miscanthus* and SRCW-supported by observations of reduced N_2O emissions after co-firing coal boilers with biomass [46]. Such emissions will depend on varying operating parameters in addition to control and emission abatement technologies. Removing energy-crop biomass from fields for combustion will also reduce the quantity of methane-release arising from in-field decomposition. Fuel preparation made a minor contribution to emissions, based on a chipping energy requirement of 0.054 GJ t^{-1} DM. This value should be robust, as it is taken from an extensive overview of biomass co-firing [46], and is similar to the value used by [58] in a case study for Irish biomass energy.

It is notable that indirect emissions are minor in the electricity LCAs. Following Hartmann and Kaltschmitt [45], construction and decommissioning GHG emissions were considered identical for electricity produced from co-fired biomass as from coal. Any additional emissions associated with retro-fit modifications for energy crop handling and co-firing at the plants would be negligible over the 20-year plus remaining plant lifetimes. Similarly, transport, irrespective of distance variation, had a minor impact on the final electricity LCA (although it is an important economic consideration for energy crops). Indirect emissions for peat electricity generation were higher, and dominated by peatland drainage emissions. This value is poorly quantified, but in any case contributes less than 4% to overall peat electricity emissions.

4.4. Total potential GHG emission savings

LCA demonstrates that cultivation would account for most of the comparatively low GHG emissions arising from energy-crop electricity generation, but these emissions could be offset through the displacement of GHG-intensive conventional agriculture and soil C-sequestration effects. In the land-use and fuel substitution permutations listed in this paper, land-use displacement contributed between 13% (SRCW displacing sheep and coal) and 41% (SRCW displacing dairy and coal) of total emission reductions. In the case of *Miscanthus* planted on tillage land, the (~100-year duration) annual soil C sequestration effect is greater than CO_2 eq. emissions arising over the entire *Miscanthus* electricity fuel-chain. Thus, this scenario of *Miscanthus* electricity generation is actually better than C-neutral.

Sensitivity analyses indicate that the GHG emission savings presented in the scenario are robust to variation in major factors such as cultivation emissions and yields. Utilisable yield assumptions applied in this paper are relatively conservative (8.8 and 11.7 t DM ha^{-1} a^{-1} for SRCW and *Miscanthus*, respectively). Variation in yields will have a greater impact on potential GHG emission reductions by altering the economic competitiveness of energy crops, rather than through life-cycle emission effects. Some of the life-cycle impacts and emissions reductions quantified here will occur outside Ireland (e.g. fertiliser manufacture), but this will also decrease the net Irish emissions associated with energy-crop electricity generation.

There is scope to further reduce the life-cycle emissions of energy-crop electricity. In terms of cultivation, the application of waste water or sewage sludge to SRCW could reduce fertiliser (and possible future water) requirements, whilst simultaneously treating waste streams [59,60]. Alternatively, energy crops could be planted on buffer strips adjacent to vulnerable water bodies, where compliance with the EU Water Framework Directive [61] may restrict conventional agricultural uses. Final delivered energy GHG-emission burdens could be reduced through more efficient conversion, such as in heat production [28], combined heat and power plants, gasification and co-firing in combined-cycle plants, or firing in dedicated power stations (e.g. combined-cycle advanced gasification). Ultimately, economic accountability for land-use GHG emissions (e.g. through inclusion in EU Emissions Trading Scheme) could result in energy-crop cultivation becoming a highly competitive land-use option.

4.5. Displacement effects

From a global perspective, the impact of 'displaced' land use will depend on whether this land use (perhaps altered) and associated GHG emissions are displaced to another country. Globally, land scarcity may create conflicts between food-crop and energy-crop cultivation. In Ireland, the large agricultural land area relative to population size, combined with the marginal economics of conventional agricultural production following CAP reform, provides an almost uniquely good opportunity for energy-crop utilisation (at scales much larger than referred to in this paper). In this paper, it is assumed that energy crops will displace economically marginal livestock and sugar-beet overproduction stimulated by past production-related CAP subsidies. Ultimately, land-use displacement by energy-crop cultivation will depend on the real or perceived farm-specific economic competitiveness of energy crops. Anticipated national-average gross margins for *Miscanthus* and SRCW were found to be competitive with gross margins from the major agricultural systems, except dairy [14]. Therefore, it may be anticipated that energy-crop cultivation could encourage additional destocking, and increase the 2.8 M t CO_2 eq. a^{-1} reduction forecast for Irish agricultural emissions between 1990 and 2010 [13]. The cultivation of SRCW on set-aside land and destocked grassland to supply wood-chip as a heating fuel is considered in [15,28].

Displacement of sugar beet was considered, as this crop is now economically unviable. While sugar beet is a potential bioethanol feedstock, the energy yields (typically around 120 GJ ha^{-1} a^{-1} of ethanol) are lower than *Miscanthus* (211 GJ ha^{-1} a^{-1} in this study) and the environmental impacts are higher. Furthermore, the peat displaced by *Miscanthus* is a more GHG-intensive fuel than the petrol displaced by bioethanol. Thus, greater GHG emission benefits (including significant soil C-sequestration) would be achieved through *Miscanthus* and SRCW utilisation. However, it would be necessary to compare the costs of GHG emission reduction via sugar-beet bioethanol with *Miscanthus* and SRCW co-firing electricity generation (or heat production) utilisation routes to determine the better strategy. Continued sugar-beet cultivation may be necessary for Ireland to comply with the EU Biofuels Directive (2003/30/EEC).

Data presented here indicate that, if energy crops were initially planted on destocked grassland, the small increase in agricultural GHG emissions associated with their cultivation would be greatly offset by large GHG emission reductions associated with coal and peat displacement. For example, SRCW planted on destocked sheep-grazing land and replacing coal electricity would displace 18,028 kg CO_2 eq. ha^{-1} a^{-1} (Table 5) compared with a 3751 kg CO_2 ha^{-1} a^{-1} (sheep-grazing LCA: Fig. 1) reduction for destocking alone (a five-fold increase in GHG emission reduction). For *Miscanthus* displacing sugar beet and peat, compared with extensification of sugar-beet area to set-aside, the GHG emission saving is nine times greater. This is in line with [62], who found that, in terms of C-mitigation, energy-crop cultivation on the 10% surplus EU arable land was three times more effective than agricultural extensification. Furthermore, there is some evidence that the extensification of livestock systems, whilst decreasing GHG emissions per hectare, may increase GHG emissions per unit product output [51,63,10]—work is needed to identify optimal spatial patterns of extensification and land-use changes in response to recent subsidy decoupling from production, considering factors such as GHG emissions, water quality and biodiversity.

5. Conclusions

The construction of full LCAs for *Miscanthus* and SRCW electricity chains confirmed that electricity produced from energy crops would be associated with a substantial (almost 90%) decrease in GHG emissions compared with conventional peat and coal electricity. In addition, GHG emissions attributable to *Miscanthus* and SRCW cultivation were substantially lower than those attributable to conventional agricultural systems. For example, *Miscanthus* and SRCW cultivation resulted in GHG emission reductions of 10,130 and 10,722 kg CO_2 eq. ha^{-1} a^{-1}, respectively, when replacing dairy systems, and 5821 and 4030 kg CO_2 eq. ha^{-1} a^{-1}, respectively, when replacing sugar-beet cultivation. To indicate the consequent potential implications for national GHG emissions, a simple scenario of 30% peat-electricity substitution with co-fired *Miscanthus*-electricity, and 10% coal-electricity substitution with co-fired SRCW-electricity, was developed. *Miscanthus* was assumed to replace sugar-beet cultivation, and SRCW assumed to replace equal areas of dairy, beef and sheep farming (land uses currently under economic pressure). This scenario resulted in a net national annual GHG emission saving of 1.9 Mt CO_2 eq. (2.8% of 2004 total emissions), equivalent to one-quarter of the emission reduction necessary for Ireland to comply with its Kyoto commitment.

If cultivation emissions were 50% higher than those calculated here, GHG emissions from energy-crop electricity would still be over 80% decreased compared with peat and coal electricity. Energy-crop electricity emissions were not particularly sensitive to yield, either, when likely cultivation emission reductions were factored into lower yield estimates. Lower yields actually resulted in higher total emission reductions, but required greater areas of land. Transport emissions and indirect emissions associated with energy conversion (power station construction, etc.) made only marginal contributions to electricity production emissions, and variation in these is unlikely to significantly deteriorate the overall GHG balance of energy-crop utilisation. Thus, energy crops have the potential to substantially reduce GHG emissions in Ireland, through utilisation of existing power stations and only a small proportion of available agricultural land.

The GHG emission reduction calculated from the scenario presented here is additional to the emission reduction forecast to arise from destocking trends between 1990 and 2010 [13], and would involve the displacement of small numbers of livestock (e.g. just 1.2% of dairy herd) and land area (1.7% of agricultural land). Energy-crop cultivation could increase GHG emission reductions arising from agricultural land destocking by a factor of up to nine, and encourage further destocking. Conversely, considering agricultural displacement increases GHG emission reductions associated with energy-crop electricity production by up to 70%. It is necessary to consider effects in both the agricultural and electricity sectors to provide the basis for an accurate and comprehensive cost–benefit analysis of energy-crop utilisation. On the basis of findings so far, it appears that encouraging farmers to cultivate energy crops should be a favourable proposition in terms of national policy goals pertaining to agriculture, the environment and energy. From an international perspective, the findings presented here suggest that economic accountability for GHG emissions could encourage utilisation of agricultural land for energy crops.

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