Life Cycle Assessment (LCA) of GHG emissions and Techno-economic Analysis of Bioenergy Production in Ireland

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Potential for Negative Emissions in Ireland (IE-NETS)
Work Package 3 Report

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Introduction

Life Cycle Assessment

Bioenergy technologies are diverse and span a wide range of options and technological pathways. However, the most favoured options and technologies will be those with the lowest life cycle emissions. Evidence suggests that options with low life cycle emissions are site-specific and rely on efficient integrated 'biomass to bioenergy' systems with sustainable land use management and governances.

Life cycle assessment (LCA) is a computational tool that can be used to evaluate the sustainability of a future biofuel industry. It is a complex tool that lies at the interface between science, engineering and policy. Transparent and accountable LCAs provide a scientific foundation for evaluating the ecological and economic sustainability of biofuels. This holistic view of biofuels is necessary to accurately assess the costs and benefits of alternative fuel systems. Biofuel policies adopted by most countries typically require GHG reduction targets to be met, which are measured through LCA. A full LCA includes cradle-to-grave emissions flows (and/or environmental impacts) starting with biomass cultivation and ending with fuel consumption.

In WP3 we use life cycle assessment (LCA) analysis as a tool to identify potential environmental impacts of end products from the various processes in the whole life cycle. It is a system to evaluate the material and energy inputs and outputs in terms of end products and emissions as well as different environmental impacts of the products during the life cycle. An LCA analysis has four basic steps; (i) a goal, scope and boundary definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation of results.

LCA methodology has been increasingly used to assess the potential benefits and/or undesired side effects of biofuels. LCA was developed as a method to compare the environmental profiles of products and services on a 'per-unit' basis (functional unit) and is, in most applications, a static approach. However, the choice of efficiency terms, life-cycle inventories and systems boundaries determines the outcomes of an LCA. Consequently, LCA must be carried out with awareness of how each component could influence the outcome. The LCA methodology is regulated by ISO 14040:2006 and ISO 14044:2006 standards which provide the principles, framework, requirements and guidelines for conducting a LCA study but fundamentally it is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Despite this standardised approach the published outputs from LCA studies show a very wide range of uncertainties that currently make it impossible to provide an exact quantification of the environmental impacts of bioenergy crops and energy production. This is largely because of the many variables which can be incorporated into any analysis and also because some of the key parameters (such as indirect effects) are not well known and strongly depend on local and climate conditions (Cherubini and Stromman, 2011).

The aim is to develop a comprehensive life cycle assessment of the GHG emissions profile of target biofuel crop cultivation in Ireland with a focus on short rotation willow and *Miscanthus*. Life Cycle Assessments are aimed at minimising the environmental impacts of emissions and resource depletion associated with the process of bioenergy production (Davis, Anderson-Teixeira, and DeLucia 2009). Conducting a full LCA for bioenergy production is important for determining the authentic environmental benefits of cultivating biofuel crops. In this work package we will update the work of Styles and Jones (2007) to calculate greenhouse gas emissions from dominant agricultural land uses with a focus on the use of marginal or less productive land for PRG or SRC.

We use a life cycle inventory (LCI) modelling package up to the point of the farm gate to assess net GHG emissions. The inventory considers all inputs and processes involving a net emission or sink of the major GHGs (CO_2, CH_4, and N_2O). This explicitly considers overall national energy system scenarios constrained to achieve net zero (or negative) emissions, implying low- or zero-GHG farm inputs and on-farm energy consumption. Proper assessment will be included of the emissions of the specific land-uses potentially being displaced, and one-off emissions (if any) associated with land-use change/biofuel crop establishment.

We also apply techno-economic analysis (TEA) to bioenergy production systems to provide a more detailed understanding of their likely economic and technical impacts, including parameters for cost-benefit assessment and evaluation of risk. This will build on and complement previous near term (up to 2020) economic analysis of bioenergy in Ireland by SEAI (2012), as well as longer term general equilibrium modelling of bioenergy development using the Irish-TIMES platform (Chiodi et al. 2015).

Techno-economic analysis

In our review of the potential of terrestrial NETS in Ireland (McGeever et al. 2019) bioenergy with carbon capture and storage (BECCS) was identified as one negative emission technology that could be viable in Ireland over the next 50 years. BECCS is the combination of two well-known technologies for climate change mitigation, bioenergy production and carbon capture and sequestration (CCS). The use of BECCS has been strongly advocated in recent years because of its potential to remove CO_2 from the atmosphere and in doing so permit the offsetting of otherwise hard to reach sources such as transport. Therefore, in the context of meeting ambitious climate change mitigation scenarios, BECCS plays an increasingly important role in the outputs of integrated assessment models (IAMs), both as an offset technology and as a means to address overshoots in emissions. However, the need for large scale deployment of BECCS presents very serious problems, relating particularly to land competition for food production, as well as CO_2 emissions associated with biomass cultivation, harvesting and processing. Consequently, there is a need for detailed assessments of the consequences of the deployment of the biomass supply chain and the conversion technologies in terms of their environmental, technical and economic impacts.

Materials and methods

The LCA methodology was applied according to the International Organization for Standardization guidelines on life cycle assessment, executed through the following steps: goal and scope definition, life cycle inventory LCI, life cycle impact assessment (LCIA), and life cycle interpretation (ISO 14044, 2006). For both *Miscanthus* and SRCW production systems, a separate individual attributional LCA model was created in Microsoft Excel.

Goal and Scope

The goal of this study was to estimate the environmental burden associated with the growing of and the energy (GJ) obtained from *Miscanthus* and short rotation coppice Willow (SRC; *Salix* sp.), whilst evaluating their performance in the context of NETS. Both *Miscanthus* and SRC, were modelled at site specific locations (1km resolution), varying in soil type and climate, across Ireland. In the case of *Miscanthus,* three cropping scenarios are analysed, the baseline scenario (S_B) which includes organic and inorganic fertiliser input; S_1, organic fertiliser input only; and S_2, inorganic fertiliser input only. The scenario with the highest environmental burden was to be determined. As this study focuses on the production of energy (GJ^{-1}) from biomass available to the end user, i.e. end user gate; it is thus considered a 'cradle to gate' LCA.

Functional unit

The function of both the *Miscanthus* and SRCW production systems is the production of biomass for energy use. It then follows that for both production systems, the functional unit (FU) in this case is '1 GJ of energy available to the end user', thus enabling comparison with other energy production systems. Energy content is commonly used as a FU in biomass for energy production systems (Murphy et al., 2014; Murphy et al., 2013; Monti et al., 2009; Styles and Jones, 2008).

System description - Miscanthus

A delimitation of the system boundary and the processes included for LCA *Miscanthus* production is illustrated in Figure 1. The system encompasses the following elements: raw material acquisition (crop cultivation and harvesting), biomass processing (pelleting), and transport to the end user.

The *Miscanthus* production model uses yield data obtained from the MiscanFor model on varying soil types across Ireland, under current climate conditions. Table 1 gives a timeline for the major field operations undertaken in *Miscanthus* production cropping cycle. Miscanthus crops are grown as a perennial with multiple harvest cycles (or rotations).

The first stage of land preparation prior to seeding involves application of herbicide to control actively growing weeds. This is then followed by subsoiling and ploughing, all of which is carried out in the autumn of year 0. In spring of year 1, prior to planting, lime is spread. The land is harrowed using a power harrow in order to ensure an adequate soil tilth (Caslin et al., 2015).

Miscanthus rhizomes are then planted at a density of 15,500 cuttings ha^{-1} using a modified potato planter. The site is consolidated by rolling and a residual herbicide applied. During the first two growing seasons (Years 1-3, Table 1) fertiliser is not applied. Fertiliser is then applied 17 times over the life of the *Miscanthus* plantation, post-harvest. The first harvest of the *Miscanthus* takes place after the 3rd growing season, in year 4 (February/March) (Table 1), with successive harvests carried out on an annual basis thereafter, as part of the 20 year cropping cycle (Table 1).

The crop is mown and left in the field to dry before baling. The bales are subsequently transported 5 km to the farmyard. It is chopped and further dried using a modified grain dryer. The *Miscanthus* is then pelleted. The processed Miscanthus is transferred to trucks and is transported to the distributor.

The elimination of the *Miscanthus* rhizomes is carried out at the end of the cropping cycle, in year 21 (Table 1). The life cycle model allocates resource demands and associated emissions for all operations shown in Table 1 evenly across the total biomass harvested over a 21-year timeline.

Table 1. Summary of field operations involved in the *Miscanthus* production cycle.

Field operation				**Year**			
	0	1	2	3	4	5 to 20	21
Pre - cultivation herbicide	✓						✓
Subsoiling	✓						
Ploughing	✓						✓
Lime application		✓					
Power harrow		✓					
Plant		✓					
Roll		✓					
Harvest					✓	✓	
Residual herbicide application		✓			✓	✓	
Fertilise					✓	✓	

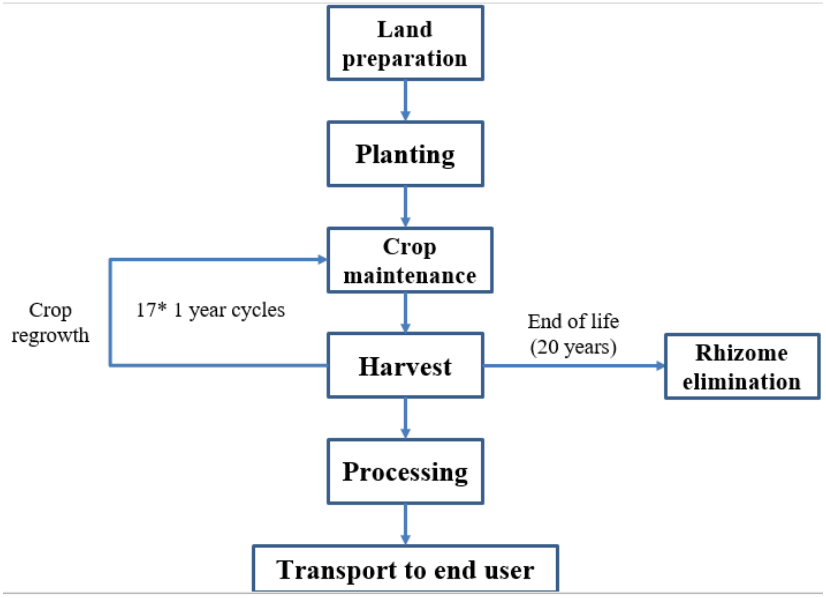

Figure 1. Production system boundary delimitation for *Miscanthus* life cycle assessment

System description – SRCW

Land preparation prior to planting SRCW was assumed to be identical to that for *Miscanthus*. The willow crop is planted with a modified potato planter to a density of approximately 16 500 cuttings ha^{-1} (Murphy et al., 2013). The site is consolidated by rolling and a residual herbicide applied. The crop is coppiced/cutback during the first growing season and further herbicide applied (Caslin et al., 2015). Inorganic fertiliser application rates were as detailed in Table 2, and was applied in the first year of each 3-year rotation (Murphy et al., 2013). Nitrogen was applied to the crop in the spring so as to minimise the amount of fertiliser taken up by competing plants (weeds) or lost through runoff (Volk et al., 2004).

Leaf litter from the willow crop is an additional source of nutrients which can be re-utilized by the growing plant (Ericsson, 1994; Baum et al., 2009). Annual leaf fall in this situation is assumed to be 3800 kg ha $^{-1}$ yr $^{-1}$ and a leaf nitrogen content of 1.5% was assumed according to Heller et al. (2003).

As part of willows' cropping cycle it is harvested every 3 years (Murphy et al., 2013). In this study willow is harvested by way of 'direct chipping', i.e. using a self-propelled forage harvester equipped with a fitment for harvesting willow (Caslin et al., 2015). It is assumed that upon harvest, the willow biomass is transported 5 km to the farm yard. The willow chip is then transferred to trucks and is transported to the 'end user' that is assumed in this instance to be located 50km from the farm.

Yield simulation model, MiscanFor

The yield simulation model MiscanFor (Hastings et al., 2008), parameterised for *Miscanthus* and willow, was used to project Irish specific *Miscanthus* and SRCW dry matter yields, at a resolution of 1 km^2. The model was run using climate data for current climatic conditions using University of East Anglia Climate Research Unit (CRU) (Hastings et al., 2008) CRU 4.2 scenario. Data for the soil parameter input to MiscanFor was obtained from the Food and Agriculture Organisation of the United Nations 'Harmonised World Soil Database (HWSD) v 1.2' (FAO, 2019).

Table 2. Summary of field operations involved in the short rotation coppice willow (SRCW)

Field operation	**Year**					
	0	1	2	3	4,7,10,13 ,16,19,22	22
Pre - cultivation herbicide	✓					✓
Subsoiling	✓					
Ploughing	✓					✓
Lime application		✓				
Power harrow		✓				
Plant		✓				
Roll		✓				
Coppice			✓			
Harvest					✓	
Herbicide application		✓	✓		✓	
Fertiliser application					✓	

Results and Discussion

The impact categories used were climate change, eutrophication (EP) and acidification (AP). For climate change impact, emissions of methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2) were calculated following the approach outlined in Rice et al. (2017) which was based on that from the carbon footprint model of O'Brien et al. (2014), certified by the Carbon Trust according to (PAS 2050) for LCA (BSI, 2011). Greenhouse gas (GHG) emissions were expressed in CO_2 equivalents (CO_2-eq) using the following global warming potential values (GWP) from

Forester et al. (2007) (as opposed to the IPCC (2014) revised guidelines, due to similarity): 1 for CO_2, 28 for CH_4 and 298 for N_2O, assuming a 100-year time horizon.

EP includes contributions from air and water emissions of ammonia and phosphorous, air emissions of nitrogen oxides, and water emissions of nitrates and phosphates. EP impact was calculated using the following generic EP factors as per van der Werf et al.(2009) in kg PO_4-equivalents, NH_3: 0.35, NO_3: 0.10, NO_2: 0.13, NO_x:0.13, P:3.06. AP includes air emissions of ammonia, sulphur oxides, and nitrogen oxides. AP impact was calculated also using the following generic AP factors as per van der Werf et al. (2009) in kg SO_2-equivalents, NH_3: 1.6, NO_2: 0.5, NO_x: 0.5, SO_2: 1.2.

With regards to N input and associated nitrogenous emissions, firstly ammonia (NH_3) released to the atmosphere through volatilization, the rate of which is outlined in Table 5. After ammonia volatilization, N_2O formation was estimated from the remaining available nitrogen from synthetic and organic sources (Table 5). While nitrate leaching under willow and *Miscanthus* plantations is low when compared with conventional agricultural crops (Murphy et al., 2013, 2014), with regards to *Miscanthus,* nitrate leaching was estimated using the IPCCs' (IPCC, 2006) emission rate of 30% of applied N from both organic and inorganic fertilizers under conventional cropping systems. Based on findings from Jørgensen et al. (2013) the rate of nitrate leaching for SRCW in this study was assumed to be 90% lower than that for *Miscanthus*. Additionally, regarding both cropping systems, 0.75% of N leached is converted to N_2O, whilst N_2O from NH_3 redeposition was estimated at 1% (Table 5).

In this assessment, for *Miscanthus*, three LCA modelling scenarios are compared; organic N fertiliser from leaf litter only, inorganic fertiliser (N, P, and K) only, and organic plus inorganic fertiliser.

It was assumed that there was no carbon sequestration to the soil (O'Brien, et al., 2014; IPCC, 2006).

Machinery and fuel consumption

Data on the productivity associated with the various field operations and their respective fuel consumption used in the cropping of both Miscanthus and SRCW was compiled on a 'best fit' basis from observations in the field.

Table 3. Field Inputs to the willow cropping system.

Activity	Input item	Frequency (per 22 year cycle)	Application rate (kg ha^{-1})	Life cycle total (kg ha^{-1})
Land preparation	Water	1	400	400
	Glyphosate	1	1.09	1.09
Planting	Cuttings	1	16,500u	16,500u
	Water	1	500	500
	Pendimethalin	1	1.09	1.09
	Chlorpyrifos	1	1.5	1.44
Maintenance	Nitrogen (N)	7	100	700
	Phosphrous	7	24	168
	Potassium	7	135	945
	Water	7	200	1400
	Pendimethalin	8[a]	1.37	10.96
Crop removal	Water	1	200	200
	Glyphosate	1	1.8	1.8

Table 4. Field inputs to *Miscanthus* cropping system.

Activity	Input item	Frequency (per 20 year cycle)	Application rate (kg ha^{-1})	Life cycle total (kg ha^{-1})
Land preparation	Water	1	200	200
	Glyphosate	1	1.09	1.09
Crop establishment	Cuttings	1	15,500u	15,500u
	Water	1	500	500
	Pendimethalin	1	1.09	1.09
Maintenance	Nitrogen (N)	14	60	840
	Phosphorous	14	9	126
	Potassium	14	58.75	822.5
	Water	14	200	2800
	Pendimethalin	14	1.37	19.37
Crop removal	Glyphosate	1	1.8	1.8
	Water	1	200	200

Table 5. Nitrogen input, emission and emission factor.

Process/source	Emission factor	Unit	Reference
Fertiliser spreading			
Ammonia	2% of CAN applied	kg NH_3/kg N	Duffy et al. (2011)
Direct nitrous oxide	0.01	kg N_2O-N/kg N	IPCC (2006)
Indirect nitrous oxide	0.01	kg N_2O-N/kg NH_3-N	IPCC (2006)
Nitrate leaching	0.3	kg N	IPCC (2006)
Nitrous oxide from leached nitrate	0.75% of leached N	kg N_2O-N	IPCC (2006)

Table 6. Miscanthus yield (t^{-1} ha^{-1}) categories and proportion of total area (ha^{-1}).

	Yield category (t^{-1} ha^{-1})					
	0-4	4-8	8-12	12-16	16-20	20-24
Percentage of total ha^{-1}	36.76	<1	26.78	33.41	2.50	<1

Table 7. Climate change impact (GWP; kg CO_2 eq), Acidification impact (AP; g So_2 eq), and Eutrophication impact (g PO_4 eq) per GJ^{-1} contained in the willow chip.

	Impact category	Unit	Land preparation	Planting	Maintenance	Harvest	Transport	Stool Elimination	Total
	GWP	kg CO_2 eq GJ^{-1}	0.126	1.277	9.617	1.638	0.213	0.047	12.917
16T	AP	g So_2 eq GJ^{-1}	0.652	1.005	52.393	10.508	1.361	0.343	66.262
	EP	g PO_4 eq GJ^{-1}	0.106	0.295	29.783	1.799	0.233	0.356	32.571
	GWP	kg CO_2 eq GJ^{-1}	0.144	1.459	10.990	1.488	0.213	0.053	14.349
14T	AP	g So_2 eq GJ^{-1}	0.745	1.148	59.877	9.549	1.361	0.392	73.073
	EP	g PO_4 eq GJ^{-1}	0.121	0.337	34.038	1.634	0.233	0.406	36.770
	GWP	kg CO_2 eq GJ^{-1}	0.202	2.043	15.387	2.062	0.213	0.075	19.981
10T	AP	g So_2 eq GJ^{-1}	1.043	1.608	83.828	13.228	1.361	0.549	101.617
	EP	g PO_4 eq GJ^{-1}	0.169	0.472	47.653	2.264	0.233	0.569	51.361
	GWP	kg CO_2 eq GJ^{-1}	0.336	3.405	25.644	3.400	0.213	0.125	33.123
6T	AP	g So_2 eq GJ^{-1}	1.739	2.679	139.714	21.814	1.361	0.915	168.222
	EP	g PO_4 eq GJ^{-1}	0.282	0.787	79.424	3.734	0.233	0.948	85.408
	GWP	kg CO_2 eq GJ^{-1}	1.008	10.214	76.933	10.092	0.213	0.374	98.835
2T	AP	g So_2 eq GJ^{-1}	5.216	6.156	416.692	31.023	0.326	1.507	460.921
	EP	g PO_4 eq GJ^{-1}	0.846	2.374	167.983	11.081	0.233	2.861	185.378

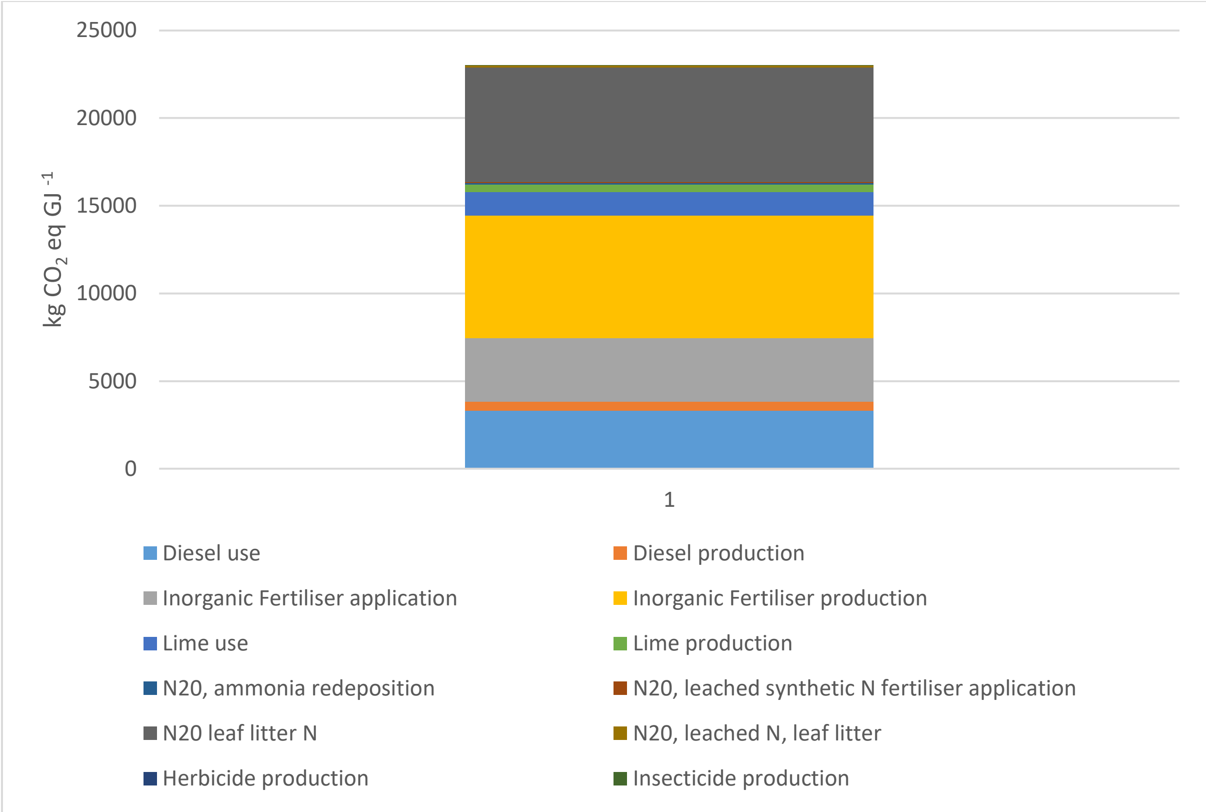

Figure 2. Process contribution to the climate change impact, (kg CO_2 eq) for energy (GJ^{-1}) from 16 oven dry tonnes of willow.

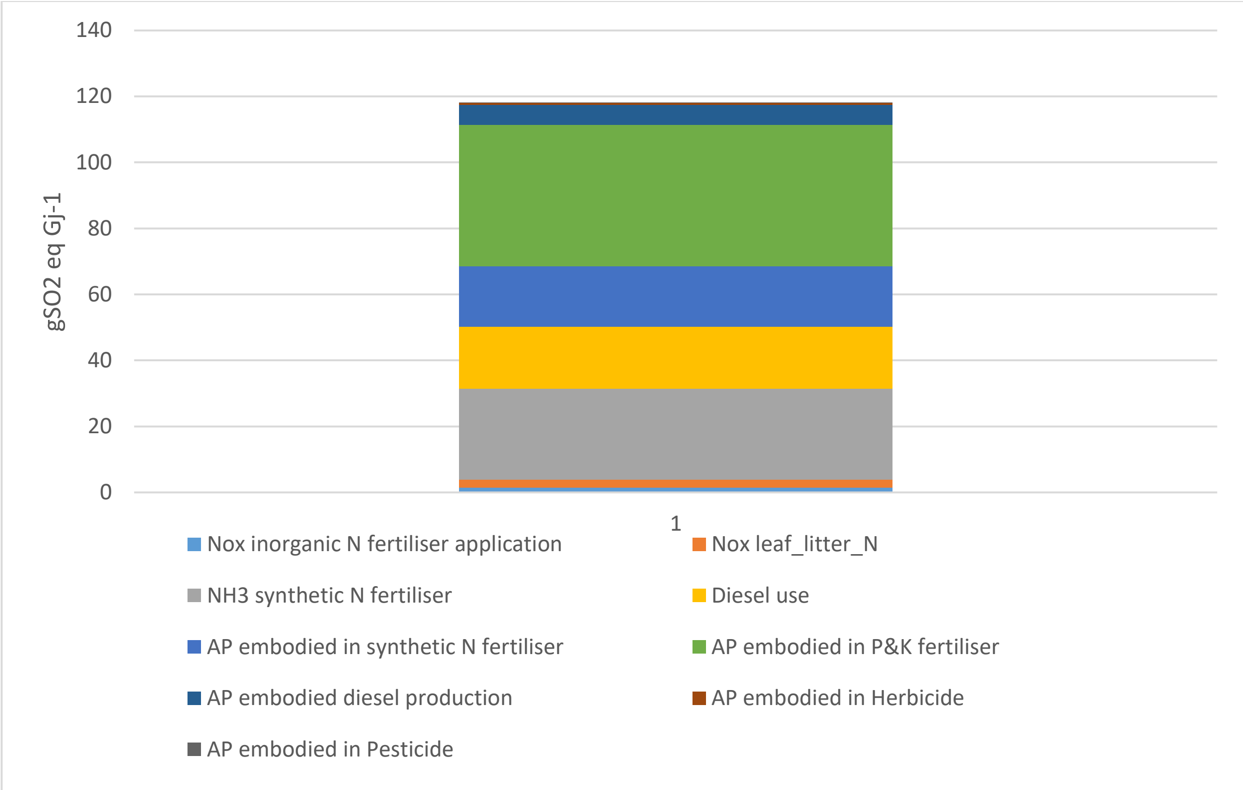

Figure 3. Process contribution to the Acidification impact (g SO_2 eq) for energy (GJ^{-1}) from 16 oven dry tonnes of willow.

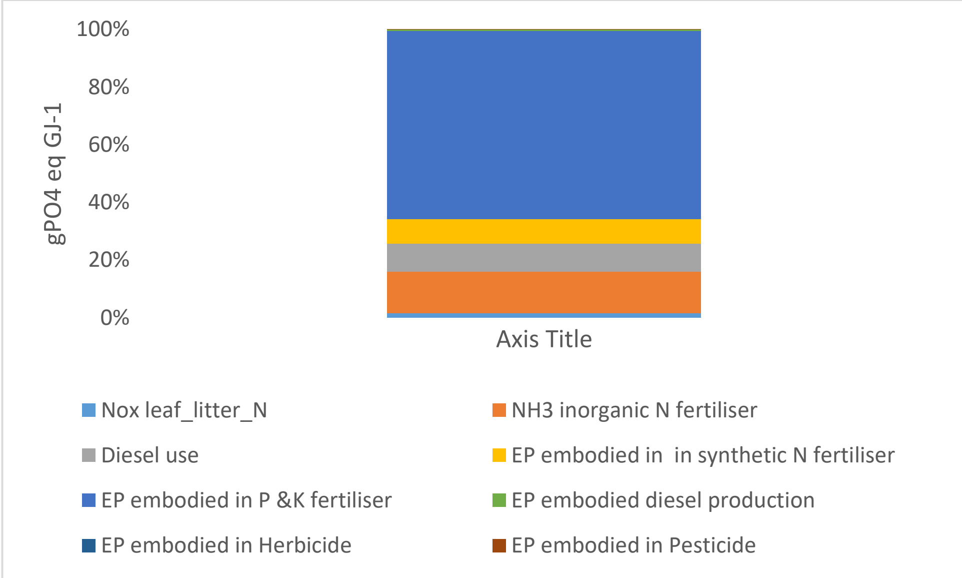

Figure 4. Process contribution to the Eutrophication impact (g SO_2 eq) for energy (GJ^{-1}) from 16 oven dry tonnes of willow.

Table 8. Climate change impact (GWP; kg CO_2 eq), Acidification impact (AP; g So_2 eq), and Eutrophication impact (g PO_4 eq) per GJ^{-1} of *Miscanthus* cultivation.

Yield category	Impact category	Unit	Land preparation	Planting	Maintenance	Harvest	Transport	Stool elimination	Processing	Total
2T (O[a]&In [b])	GWP	kg CO_2 eq GJ^{-1}	0.63	7.13	63.86	1.09	0.22	0.26	5.84	79.04
	AP	g So_2 eq GJ^{-1}	3.64	4.74	5141.35	7.01	1.38	1.92	14.76	5174.79
	EP	g PO_4 eq GJ^{-1}	0.59	1.07	1123.01	1.20	0.24	0.30	1.15	1127.55
2T (In)	GWP	kg CO_2 eq GJ^{-1}	0.63	6.22	50.08	1.09	0.22	0.26	5.84	64.35
	AP	g So_2 eq GJ^{-1}	3.64	4.43	5136.78	7.01	1.38	1.92	14.76	5169.92
	EP	g PO_4 eq GJ^{-1}	0.59	0.99	1123.21	1.20	0.24	0.30	1.15	1127.67
14T (O&In)	GWP	kg CO_2 eq GJ^{-1}	0.09	1.02	9.12	0.30	0.22	0.04	5.84	16.62
	AP	g So_2 eq GJ^{-1}	0.52	0.68	734.48	1.90	1.38	0.27	14.76	753.98
	EP	g PO_4 eq GJ^{-1}	0.08	0.15	160.43	0.33	0.24	0.04	1.15	162.42
14T (In)	GWP	kg CO_2 eq GJ^{-1}	0.09	0.89	7.15	0.30	0.22	0.04	5.84	14.52
	AP	g So_2 eq GJ^{-1}	0.52	0.63	733.83	1.90	1.38	0.27	14.76	753.29
	EP	g PO_4 eq GJ^{-1}	0.08	0.14	160.26	0.33	0.24	0.04	1.15	162.24
22T (O&In)	GWP	kg CO_2 eq GJ^{-1}	0.06	0.65	5.81	0.25	0.22	0.02	5.84	12.84
	AP	g So_2 eq GJ^{-1}	0.33	0.43	467.40	1.59	1.38	0.17	14.76	486.06
	EP	g PO_4 eq GJ^{-1}	0.05	0.10	102.09	0.27	0.24	0.03	1.15	103.93
22T (In)	GWP	kg CO_2 eq GJ^{-1}	0.06	0.57	4.55	0.25	0.22	0.02	5.84	11.50
	AP	g So_2 eq GJ^{-1}	0.33	0.40	466.98	1.59	1.38	0.17	14.76	485.61
	EP	g PO_4 eq GJ^{-1}	0.05	0.09	101.98	0.27	0.24	0.03	1.15	103.81

[a] Organic Nitrogen (N)

[b] Inorganic nitrogen (N)

Discussion

The aim of this analysis was to identify hotspots in the production chains of *Miscanthus* and willow in greenhouse gas emissions and environmental impacts. As in previous studies by Styles and Jones (2008) and Murphy at al. (2013) maintenance and processing of both crops were the stages of the life cycle which contributed most to the impact categories; global warming potential, acidification potential , eutrophication potential ,and energy demand. The pelleting of the harvested *Miscanthus* contributed most to the life cycle GHG emissions as this process requires a large quantity of energy in the form of electricity. However there are large variations in the reported energy requirements for alternative processes for compressing *Miscanthus* such as briquetting (Murphy et al., 2013), suggesting that alternative methods for processing *Miscanthus* before transport need to be investigated.

Another significant contributor to each of the impact categories for both crops is their maintenance, and in particular the production and application of synthetic fertilisers. The production of synthetic fertilisers is an energy intensive process utilising non-renewable fossil fuels. In relation to *Miscanthus* production this raises an important issue about the requirements that its cultivation had for fertiliser inputs. A characteristic of perennial herbaceous rhizomatous grasses like *Miscanthus* is their ability to continuously re-mobilise nutrients between various organs of the plant as the growing season progresses. Although the life span of the plant can be more than twenty years, its stems and leaves function for only one season. The only permanent organ is the rhizome which functions in vegetative propagation and the storage of nutrients. The internal recycling of nutrients between above- and below-ground organs allows the harvesting of biomass with a low nutrient content, but also reduces the demand for nutrients for renewed growth which is normally met through application of fertilisers.

The nutrient normally applied in greatest abundance to crops is nitrogen but another feature reducing the demand for nitrogen in *Miscanthus* is the C_4 photosynthetic mechanism which relies on a very effective photosynthetic enzyme, PEP-carboxylase for assimilating CO_2 (Jones, 2011). The presence of PEP-carboxylase means that for the same amount of photosynthesis as non-C_4 plants, *Miscanthus* has to allocate far less nitrogen to producing the enzyme required for CO_2 fixation.

As a result of it utilising C_4 photosynthesis and achieving an efficient re-cycling of nutrients *Miscanthus* has very low nitrogen requirements and limited need for fertiliser applications. Indeed, in some agronomic trials there is evidence that *Miscanthus* can be cropped for several years before there is a requirement for added nitrogen fertiliser. For example, Christian et al (2008) grew *M. x giganteus* for 14 successive harvests in the south of England and found that fertiliser N application had little influence on yields, which reached 17.7 t ha^{-1} at their peak. It was suggested however, that other nutrients such as phosphorus and potassium should be added at low levels to avoid depletion of soil reserves. In contrast to this evidence for little or no requirement for nitrogen, other trials, particularly in the USA, but also in Mediterranean

Europe (Cosentino et al., 2007), have shown a significant increase in yields of stands of *Miscanthus* when nitrogen fertiliser was added. For example, in a trial in Illinois USA, Arundale et al. (2014) found that *M. x giganteus* yield increased significantly from 23.4 t ha^{-1} with zero fertiliser to 28.9 t ha^{-1} (+25%) at an annual application rate of 202 kgN ha^{-1}. However the proportional increase in yield per unit of added N is small in *Miscanthus* compared with other C_4 crops such as maize and switchgrass (Heaton et al., 2004), and consequently it is suggested that this response to added fertiliser is unlikely to be economically worthwhile. In conclusion, it appears that there are requirements for low levels of fertiliser to maintain yields of *Miscanthus* but there are very large site to site variations which make generalisations and advice on optimum fertiliser rates extremely difficult to make. In Ireland, Murphy et al., (2013) suggest that inputs of nitrogen are required for a reasonable yield (circa 11 t ha^{-1} yr^{-1}), although the amounts required are uncertain. Clearly, further research is required to determine more precisely the level of fertiliser required and what the spatial variation is in this requirement. An additional factor is that biosolid fertiliser may have beneficial effects in substituting for synthetic fertiliser although its use will increase acidification and eutrophication potential.

Although willow is less efficient in its use of nitrogen than *Miscanthus* and thus requires significant applications, which result in N_2O emissions, the application of biosolids to the crop is an alternative fertiliser. Although there are still emissions associated with biosolid applications the high energy use in production of artificial fertiliser is avoided. However using biosolids in the place of synthetic fertiliser increases both acidification and eutrophication potential significantly. In essence, the use of biological fertiliser in place of synthetic fertiliser improves the energy performance of the system while negatively affecting each of the environmental impacts (Murphy et al., 2013).

As outlined above, the economic features of the biomass supply chain and conversion technologies can be reflected through a techno-economic assessment (TEA), where the production costs of the process is summarised to allow comparisons of different biomass sources and their conversion processes to produce energy.

Biomass is the only renewable source of energy that can be directly to high value end products in liquid, solid or gas form using thermochemical conversion technologies. The thermochemical conversion of biomass to useful end products can occur through the processes of pyrolysis, gasification, liquefaction, combustion, carbonisation and co-firing. The implementation of any of these processes depends mainly on the cost-competitiveness of biomass-based fuels and chemicals compared to those produced from conventional fossil sources. TEA of biomass thermo-chemical conversion technologies is important for its development and commercialisation, and one of the key outcomes of a TEA is the cost of producing fuels and chemicals. Production costs can be estimated by developing discounted cash flow sheet models for a biorefinery (Patel, Zhang and Kumar, 2016). The production costs are specific to the chosen thermochemical conversion technologies and their products. This complexity of analysis is beyond the scope of the current review. Therefore, the TEA we have carried out is based on a review of the literature which is relevant to the scenarios we have adopted for the bioenergy production chain and the utilisation of the biomass for energy production linked with CCS. In identifying plausible scenarios for the development of BECCS in Ireland we have focussed on the second generation bioenergy crops, *Miscanthus* and short rotation coppice willow which have been shown to provide higher biomass yields and more favourable energy input/output ratios. We also project two alternative bioenergy production pathways for BECCS based on: (a) a centralised energy system (CES) of large-scaled biomass power stations located where existing power plants are currently found and (b) a distributed energy system (DES) of combined heat and power (CHP) stations distributed to meet the heat and power demands in the future. Initially it is envisioned that the centralised energy systems will co-fire biomass with peat or coal. Recently, Albanito et al. (2019) have assessed the mitigation potential and environmental impact of both centralised and distributed BECCS in Great Britain and found that the technical mitigation potentials from BECCS leads to projected CO_2 reductions of approximately 18 and 23 Mt CO_2/year from the centralised and distributed energy systems respectively.

Centralised energy systems in Ireland currently combust fossil fuels or peat for production of electricity. Several boiler types can be used for biomass combustion for power generation. Generally, pulverised coal-fired boiler with a biomass feedstock co-fired with coal gives a lower cost of electricity than do fluidised bed boilers. A solely biomass-fuelled power plant normally has a higher cost of electricity than a coal fired plant when the price of biomass is higher than coal (Patel, Zhang and Kumar, 2016). De and Assadi (2009) report on the results form a number of pilot plant tests which have assessed the technical and economic feasibility of biomass co-firing in existing coal boilers. They have developed a techno-economic model on the basis of the experiences of these pilot plants to assess the economics of biomass co-firing. The model estimates both the total additional costs as well as additional specific costs. A sensitivity analysis was then carried out to find the effects of different operating and logistic parameters on additional costs. The most significant conclusion from this sensitivity analysis was that the CO_2 emission decreases and additional costs of retrofitting for biomass co-firing increases with increasing capacity of the plant. Furthermore, although the prices of coal and biomass will have some effects on the economics of biomass co-firing, the effects are not that significant on additional specific costs. In addition, it was found that increasing the mass of biomass co-fired with the coal gives greater reductions in CO_2 emissions but this is accompanied by an increase in total as well as specific costs.

For the case of distributed energy supply, CHP systems involve the simultaneous production of electrical power and thermal energy such as hot water and space heating. Making efficient utilisation of fuel energy by producing electricity and heat, biomass CHP designs could reach overall efficiencies of over 80%, providing an opportunity to make significant cost savings and CO_2 emission reductions compared with traditional electricity only systems. The basic biomass CHP system consists of four major components; biomass receiving and preparation, biomass conversion, power generation and heat recovery. Huang et al., (2013) compared two

CHP systems (Organic Rankine Cycle (ORC) based and biomass gasification based) for generating heat and electricity. It was found that the overall efficiencies of the OTC based CHP systems are 76% when willow chip was used and 81% with *Miscanthus*. For the biomass gasification based CHP system the overall efficiencies were 58% with willow chip and 64% with *Miscanthus*. The differences between feedstocks was found to be due to the moisture content. The main conclusions from Huang et al. (2013) were that it is technically and economically feasible to use willow chips and *Miscanthus* in both types of CHP plants but that the capital costs of the ORC based CHP systems are much higher than that of the biomass gasification CHP systems. Furthermore, the willow and *Miscanthus* CHP generated CO_2 emissions were between 421 and 562 g/kW h compared with advanced coal fired electricity power station CO_2 emissions of 782 g/kW h.

Our literature review of assessments of the consequences of the deployment of the biomass supply chain and the conversion technologies in terms of their environmental, technical and economic impacts have highlighted the complexity of the issues relating particularly to the management of the biomass supply chain. In a whole-systems analysis of the BECCS value chain associated with cultivation, harvesting, transport and conversion in dedicated biomass power stations in conjunction with CCS of a range of biomass sources, including *Miscanthus* and willow, Fajardy and Mac Dowell (2017) found that the effects of direct and indirect land use change were the key determinants of the viability of a BECCS project. This meant that the effectiveness of a BECCS plant, in terms of its lifetime removal of CO_2 from the atmosphere, was observed to be highly case specific and the viability of BECCS as a negative emissions technology option depends entirely on the choices made throughout the supply chain. Fajardy and Mac Dowell (2017) concluded that improvements in the sustainability of BECCS could be achieved, in particular, by measuring and limiting the impacts of direct and indirect land use change, minimising biomass transport, and maximising the use of carbon neutral/negative fuels.

The life cycle assessment and techno-economic analysis of bioenergy production from energy crops reviewed here can be used to assess the level of sustainability of the supply chain taking into account the criteria set out in the recast Renewable Energy Directive (RED II) and other environmental, economic and social indicators. In Ireland, for biofuels to be eligible to count towards the national 2020 renewable energy targets, they must meet the sustainability criteria as defined in the RED Articles. In essence they must meet minimum life cycle GHG savings and feedstocks cannot be grown on peatlands, or land with a high biodiversity value or land with high carbon stocks. Recently in the SEAI (2019) report on 'Sustainability Criteria, Options and Impacts for Irish Bioenergy Resources' typical GHG emission values have been calculated for a representative range of supply chains in the Irish context, including values for both *Miscanthus* and willow, neither of which have default values in RED II. They conclude that these perennial energy crops used as feedstocks for bioenergy supply chains have emission values considerably better than the RED II default values.

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