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Title: Energy requirements and environmental impacts associated with the production of short rotation willow (*Salix sp.)* chip in Ireland

Running title: SCRW - energy requirement and environmental impact

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Abstract

Willow salix sp. is currently cultivated as a short rotation forestry crop in Ireland as a source of biomass to contribute to renewable energy goals. The aim of this study is to evaluate the energy requirements and environmental impacts associated with willow (*Salix sp.)* cultivation, harvest, and transport using life cycle assessment (LCA). In this study only emissions from the production of the willow chip are included, end-use emissions from combustion are not considered. In this LCA study, three impact categories are considered; acidification potential, eutrophication potential and global warming potential. In addition the cumulative energy demand and energy ratio of the system are evaluated. The results identify three key processes in the production chain which contribute most to all impact categories considered; maintenance, harvest and transportation of the crop. Sensitivity analysis on the type of fertilizers used, harvesting technologies, and transport distances highlight the effects of these management techniques on overall system performance. Replacement of synthetic fertiliser with biosolids results in a reduction in overall energy demand, but raises acidification potential, eutrophication potential, and global warming potential. Rod harvesting compares unfavourably in comparison with direct chip harvesting in each of the impact categories considered due to the additional chipping step required. The results show that dedicated truck transport is preferable to tractor-trailer transport in terms of energy demand and environmental impacts. Finally, willow chip production compares favourably with coal provision in terms of energy ratio and global warming potential, while achieving a higher energy ratio than peat provision but also a higher global warming potential.

1 Introduction

1.1 Bioenergy targets, policy and uptake in Ireland

Biomass, a source of renewable energy, has received much attention in recent years as many countries endeavour to reduce greenhouse gas (GHG) emissions and the reliance on dwindling fossil fuel resources. In an effort to develop a sustainable energy economy and reduce GHG emissions, the European Union adopted a series of targets to be achieved by 2020; a 20% reduction in GHG emissions, a 20% increase in energy efficiency, and 20 % of the overall share of energy to come from renewable sources (European Commission, 2007). These targets became mandatory in 2009 with the publishing of the EU Renewable Energy Directive (European Commission, 2009). Each country in the EU was assigned different targets in order to achieve the overall target for Europe. Ireland's mandatory renewable energy target is 16% of gross final consumption to come from renewables by 2020 (European Commission, 2009). The Irish government first outlined its commitment to bioenergy by publishing the Government White Paper on Energy in 2007 which laid out strategic goals for sustainable energy production (Department of Communications Marine and Natural Resources, 2007). In an effort to promote the use of bioenergy in Ireland and to contribute to meeting the EU targets outlined above, the Government set out to implement co-firing of biomass at the three peat-fired electricity generating plants owned by the state. The co-firing targets are limited to cofiring 30% of the maximum rated capacity in any plant until 2017, 40% between 2017 and 2019, and 50% thereafter (Department of Communications Energy and Natural Resources, 2010). Three hundred kilotonnes of biomass will be required to achieve 30% co-firing at Edenderry power plant alone. In order to meet this demand, additional quantities of biomass to those currently co-fired will need to be obtained.

Short rotation coppice willow (*Salix sp.)* (SRCW) has been cultivated as an energy crop in Ireland which can help meet the biomass demand of the 3 peat-fired power plants. In order to promote the cultivation of willow among farmers a bioenergy scheme was introduced in 2007 which offers financial support towards the establishment of willow crops (Dillon, 2011). Similarly, Bord na Mona (operator of Edenderry power plant), offers supports to farmers willing to establish a willow crop and supply it to the power plant. These incentives have led to an increase in willow planting since their inception as shown in figure 1. There are currently more than 800 ha of willow crops planted in Ireland.

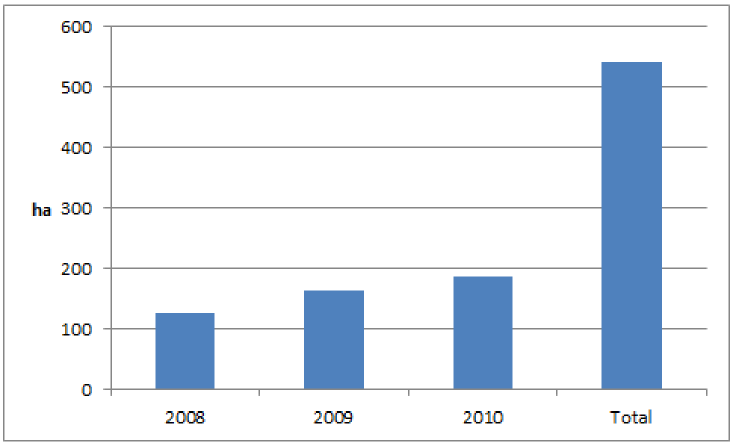

Figure 1 - Area of willow planted under the bioenergy scheme until 2010 (Dillon, 2011)

In 2010, 5,208 tonnes of willow chip were co-fired with peat in Edenderry power plant, representing 5.4% of total biomass co-fired on a mass basis. With the co-firing target increasing to 30% by 2017, a substantial increase in the area of energy crop plantations will be required. A study by Mola-Yudego and Pelkonnen (2008) on willow uptake in Sweden highlights the importance of policy measures including incentives in promoting the uptake of energy crops. As such, the incentives offered in Ireland may encourage similar uptake as in Sweden, which is now the European leader in short rotation willow plantations for energy production with the establishment of more than 14,000 ha on agricultural lands (González-García *et al.*, 2012b).

1.2 Suitability to Irish conditions

In context of climate and soils, willow (Salix) is the most suitable woody biomass crop for Ireland and for many other temperate regions of the World. Willow coppice has a high water requirement, in line with other conventional agricultural crops (Jørgensen & Schelde, 2001), and hence requires a good moisture retentive soil. Areas with an annual rainfall of 900-1,100mm are optimal for willow production, as well as areas where the crop has access to ground water (Teagasc, 2010). A study by Lindroth and Båth (1999) highlights water as a limiting factor in achieving high yields. According to Met Éireann statistics, the vast majority of Ireland receives upwards of 800 mm of rainfall per year (Met Éireann, 2012). Therefore, water availability does not represent a constraint in Irish conditions.

1.3 Justification for willow

The production and use of SRCW as a source of renewable energy has numerous benefits which contribute to its sustainability, environmentally, economically, and ecologically;

Willow (Salix. Sp.) is suitable for cultivation on medium fertility sites, thus not competing for the most fertile land which is currently used for food production (Helby et al., 2004). The long life-span of willow crops (20 plus years) allows the accumulation of soil carbon in mineral soils, as well as promoting stable nutrient cycling and soil biological activity, resulting in increased soil fertility when compared to conventional agricultural crops (Abrahamson et al., 1998, Börjesson, 1999a, Helby et al., 2004, Rowe et al., 2009). In addition, the cultivation of willow promotes a higher biodiversity when compared to conventional agricultural crops (Perttu, 1998, Sage, 1998, Schulz *et al.*, 2009).

Willow crops are also known for their bioremediation potential. Willow has been proven to effectively take up nutrients and heavy metals (Börjesson, 1999a, Dimitriou & Aronsson, 2011, Klang-Westin & Eriksson, 2003, Perttu, 1998). Cultivation of willow can therefore be used to treat a number waste sources; wastewater, municipal waste, sewage sludge, distillery effluent. Willow is particularly appropriate to treat these types of waste as it is not a food crop, thereby not threatening contamination in the food chain (Curley, 2010).

The use of SRCW as an energy source has been shown to be more favourable than the use of fossil fuels in terms of GHG emissions and energy requirements (González-García *et al.*, 2012a, Heller *et al.*, 2004, Perttu, 1998). Furthermore, willow also performs positively in comparison to other biomass sources such as annual food crops, sugar beet and oil seed production (Börjesson, 1996).

The economics of willow production can be improved if the crop is used for waste treatment as outlined above. Waste application allows an avoidance of fertilizer costs, and the gross profit margin increases further if compensation is paid to the farmer for waste treatment, however, currently this is not common practice in Ireland (Börjesson, 1999b, Dimitriou & Rosenqvist, 2011, Rosenqvist & Dawson, 2005). A survey carried out by Augustenborg (2012), has shown high willingness of farmers to adopt energy crops in Ireland, with over 70% of respondents indicating interest in producing energy crops.

1.4 Why Life Cycle Assessment?

Despite the environmental benefits associated with willow production as reported above, intensive willow coppice cultivation involves potential negative environmental effects. The life cycle of a willow crop managed for energy purposes requires the use of energy and raw materials in several respects; in the extraction of raw materials (fuels, minerals), in production and transportation of system inputs (fertilizers, pesticides), and in field operations required for crop cultivation. Willow crop cultivation also results in emissions to air, soil, and water which may have effects on the environment. It is essential that all effects, positive and negative, are considered in a holistic manner to enable a comprehensive evaluation of the system. LCA is a tool which can be used to assess the sustainability of agricultural and energy production systems in terms of energy balance and environmental impacts. LCA allows the holistic evaluation of the environmental impact of a product or system over its entire life-cycle, from raw materials acquisition through processing, to the point of final consumption and disposal. In LCA, the material and energy inputs for each step in the life cycle are quantified, and related to the resulting outputs in the system inventory. Potential environmental impacts resulting from the system are then predicted based on this inventory. The holistic nature of LCA analysis allows the identification of hotspots in the system; points of critical contributions to key environmental impacts. A wide range of LCA literature exists evaluating the benefits of energy crops systems (Butnar *et al.*, 2010, Gasol *et al.*, 2010, Monti *et al.*, 2009, Rafaschieri *et al.*, 1999), with a number of them focusing on willow production (González-García *et al.*, 2012b, Heller *et al.*, 2003, Lettens *et al.*, 2003, St. Clair *et al.*, 2008, Styles & Jones, 2008).

The aim of this study is to evaluate the energy requirements and environmental impacts associated with the cultivation, harvest, and transport of willow (*Salix sp.)* for energy utilisation in Ireland. The paper presents detailed life cycle inventory (LCI) data for willow cultivation in Ireland. The paper considers a number of scenarios based on; synthetic fertilizer and biosolid application, chip and whole rod harvesting, and transport distances. Cherubini et al. (2009) have recommended that the energy and GHG balances of biomass to energy systems should always be contrasted against fossil fuel systems. This allows comparison of the potential benefits/drawbacks of the bioenergy system in question. As such, the results of this LCA are compared to some common fossil fuels including coal and peat, feedstocks with which biomass is commonly co-fired in Ireland (Heller *et al.*, 2004, Mann & Spath, 2001, Sebastián *et al.*, 2010, Styles & Jones, 2008).

2 Materials and Methods

The LCA is carried out in accordance with the steps outlined in the International Standards on life cycle assessment, namely; goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation (ISO 14040, 2006, ISO 14044, 2006). The LCA software SimaPro v7.3.2 (PRé Consultants, 2011) was used to construct the LCA model and undertake the impact assessment calculations.

2.1 Goal and Scope

The aim of this study is to evaluate the energy requirements and environmental impacts associated with willow (*Salix sp.)* cultivation, harvest and transport. Different management practices based on the application of synthetic and organic fertilizers are compared. Two methods of harvesting, direct chip and whole rod, are analysed. Two transport distances are evaluated; 50 km and 100 km. The scenario with the highest energy ratio will be determined. It is envisaged that the results of this study will help to establish the most environmentally friendly pathways for willow cultivation and harvest. As this study focuses on the production of biomass and transport to the end user gate it is thus considered a 'cradle to gate' LCA.

2.1.1 Functional unit

The function of the SRCW system is the production of biomass for energy use. The functional unit generally used in other LCA studies on biomass production is area of crop production (hectare) (Goglio & Owende, 2009, González-García *et al.*, 2012b, Heller *et al.*, 2003, Styles & Jones, 2008). However, as the function of the system being studied is for energy use, and the results are to be compared with fossil fuels, the functional unit in this case is '1 GJ of energy contained in the willow biomass'. Using a measure of energy contained in the feedstock allows the energy productivity of the system to be analysed in comparison with other sources of fuel (Goglio *et al.*, 2012, Nemecek *et al.*, 2011).

2.1.2 System description

The LCA considers three aspects of the supply chain; willow cultivation, harvesting and transport. All of the field activities, from land preparation, to maintenance, harvesting and transport have been considered, as can be seen in the system diagram in figure 2. All of the inputs (material, fuel, energy) and outputs (product flow, and emissions to air, soil, water) for each of the unit operations in the supply chain are quantified and included in the LCA.

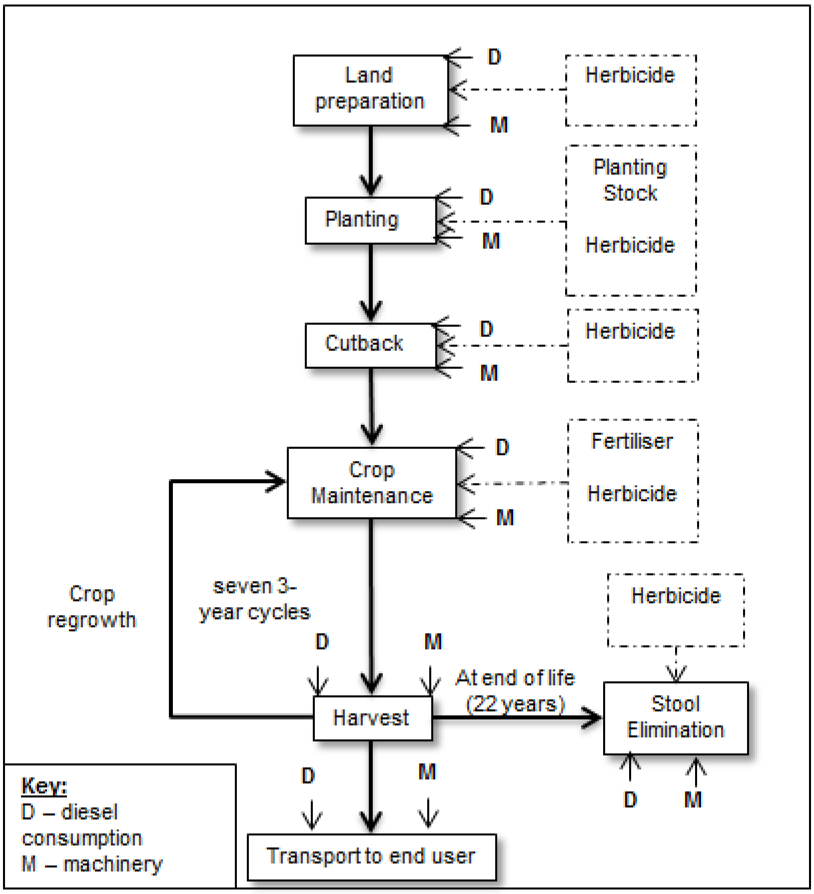

Figure 2 - System boundary of willow cultivation. Dotted lines denote material inputs to the system.

Description of crop production cycle outlined in figure 2:

The ground is prepared prior to seeding. This involves application of herbicide to control actively growing weeds, ploughing, and finally disking to prepare a stale seedbed for planting. The willow crop is planted with a modified potato planter to a density of 16,500 cuttings per hectare. The site is consolidated by rolling and a residual herbicide applied. The crop is cutback during the first growing season and further herbicide applied. Fertiliser is not applied during the first two growing seasons. Beyond this, fertilizer is applied 7 times over the life of the willow plantation (after every 3 year harvest). Herbicide is also applied at this stage. Nitrogen is added to the growing plants in the spring with the aim of minimising the amount of fertilizer taken up by competing plants (weeds) or lost through runoff (Volk et al., 2004). The application of synthetic fertilizers and biological fertilizers are compared in this study. Willow is harvested on a 3-yearly basis. Upon harvest, the willow biomass is transported 5 km to the farm yard. Two harvesting methods are compared in this study; direct chipping, and whole rod harvesting followed by chipping. In the case of rod harvesting, the rods are chipped at the farm yard. The willow chip is transferred to trucks and is transported to the distributor. In this analysis three transport scenarios are compared; delivered 50 km and 100 km by truck, and delivered 50 km by tractor-trailer. The willow crop is removed from the site at the end of the crops life (approximately 22 years) by the application of herbicide such as glyphosate followed by ploughing. This leaves the majority of the root system in place without damaging the soil structure. (Teagasc, 2010). Once the willow chip is deposited at Edenderry power plant, the assumed end user in this study, the willow is mixed with peat and co-fired immediately, therefore no drying occurs. Each scenario is outlined in Table 1, with scenario 1 representing the base case.

Table 1 – Willow production scenarios

Scenario	Fertiliser Type	Harvest Type	Transportation Method	Transportation Distance
1	Synthetic	Direct Chip	Truck	50 km
2	Biological	Direct Chip	Truck	50 km
3	Synthetic	Rod	Truck	50 km
4	Biological	Rod	Truck	50 km
5	Synthetic	Direct Chip	Tractor	50 km
6	Biological	Direct Chip	Tractor	50 km
7	Synthetic	Rod	Tractor	50 km
8	Biological	Rod	Tractor	50 km
9	Synthetic	Direct Chip	Truck	100 km
10	Biological	Direct Chip	Truck	100 km
11	Synthetic	Rod	Truck	100 km
12	Biological	Rod	Truck	100 km

2.2 Inventory Analysis

Data specifically relating to willow production in Irish conditions is used wherever possible. Where this is not possible, standard data for willow production reported in the literature is used.

The SRCW production cycle in this model is based on data from Teagasc Short Rotation Coppice Willow Best Practice Guidelines (Teagasc, 2010), and other LCA studies (Heller *et al.*, 2003, Jungbluth *et al.*, 2007). This data describes the inputs required and machinery operations over the lifetime of the willow plantation (22 years). Table 2 outlines frequency of field operations over the lifetime of the crop.

Table 3 outlines the inputs over the lifetime of the cropping system.

2.2.1 Machinery and fuel consumption

Data regarding the manufacture and fuel consumption of conventional agricultural machinery used in willow cultivation were obtained from a report by Nemecek et al. (2007). For machinery specifically related to willow production, not contained in the ecoinvent databases, other sources of data were used (Association d'Initiatives Locales pour l'Energie at l'Environnement, 2007, Lechasseur & Savoie, 2005). Data on tractor and trailer manufacture and use comes from the ecoinvent database (Spielmann *et al.*, 2007).

Most of the air emissions from biomass supply chains are due to the combustion of fossil fuels in machinery engines, and measurement of these emissions in non-laboratory conditions is difficult (Hansson *et al.*, 2003). Data regarding air emissions from field operations are obtained from Nemecek et al. (2007). Emissions from the willow harvesters were estimated based on methods used in Nemecek et al. (2007) and fuel consumption data in published literature (Association d'Initiatives Locales pour l'Energie at l'Environnement, 2007, Lechasseur & Savoie, 2005).

Table 2 – Summary of field operations and associated machinery data

		Machinery data[a]		
Field operation	Frequency of operation (per 22 year cycle)	Productivity (h/ha)	Fuel consumption (l/h)	Fuel consumption (l/ha)
Pre-ploughing herbicide	1	0.7	3	2.1
Plough	2	2.1	14.8	31.08
Disk	1	1.2	11.4	13.68
Plant	1	5.3	2	10.6
Roll	1	0.9	4.2	3.78
Harvest	7		See table 4	
Herbicide	8	0.7	3	2.1
Fertilise	7	1.5	4.2	6.3

[a](Nemecek et al., 2007)

Table 3 - Data summary of inputs to cropping system (Teagasc, 2010)

Plan	Input	Frequency (per 22 year cycle)	Application rate (kg/ha)	Total (kg/ha) over life cycle
Land preparation	Water	1	400	400
	Glyphosate	1	1.98	1.98
Crop Establishment	Cuttings	1	16500u	16500u
	Water	1	500	500
	Pendimethalin	1	1.09	1.09
Cutback	Water	1	200	200
	Pendimethalin	1	1.37	1.37
Maintenance	Water	7	200	1400
	Nitrogen	7	120	840
	Phosphorous	7	15	105
	Potassium	7	10	280

	Pendimethalin	7	1.37	9.59
Crop removal	Water	1	200	200
	Glyphosate	1	1.8	1.8

2.2.2 Field inputs

Nursery stock production was modelled based on data from Jungbluth, Frischknecht et al. (2007) and Heller, Keoleian et al. (2003).

Nitrogen, phosphorus and potassium fertilizer data was obtained from the Danish LCA Food Database (Nielsen *et al.*, 2003). The nitrogen fertilizer plant does not include catalytic N_2O cleaning. The application of biosolids (sewage sludge) as a soil amendment was modelled according to Galbally et al. (2012) and Curly (Curley, 2010). Average values for the nutrient content of biosolids were obtained from McGrath et al. (2000). Nutrient availability from biosolids were assumed to be 40% of N (Irish Government, 2009) and 46% of P (Plunkett, 2010) contained in the biosolids. The biosolids were assumed to have been pre-treated by anaerobic digestion, followed by storage and transportation of 15 km according to Akwo (2008) and Hospido et al. (2005).

The annual leaf litter from the willow crop represents a further source of nutrients which can be re-utilised by the growing plant (Baum *et al.*, 2009, Ericsson, 1994). Annual leaf fall in this case is assumed to be 3,800 kg ha^{-1} yr^{-1} and a leaf nitrogen content of 1.5% was assumed according to Heller, Keoleian et al. (2003).

Data on pesticide manufacture was obtained from Nemecek et al.(2007).

2.2.3 Field emissions

The cultivation of willow and the application of fertilizers result in emissions to air, soil and water.

The ammonium contained in fertilizers can be released to the atmosphere as ammonia (NH_3) through the process of volatilisation. Rates of volatilisation depend on a number of factors; fertilizer type, soil type and pH, and weather conditions (Heller *et al.*, 2003). In this study, NH_3 volatilisation is assumed to be 2% of applied nitrogen according to sources (Cherubini *et al.*, 2009, Nemecek *et al.*, 2007). For the application of biosolids, it is assumed that 26% of the N contained in the biosolids is released as ammonia according to Nemecek, Kägi et al. (2007).

Nitrous oxide (N_2O) is produced naturally as a product in the denitrification and nitrification processes by soil micro-organisms. The addition of nitrogen to the cropping system in the form of both synthetic and biological fertilizers enhances N_2O formation. N_2O is a powerful greenhouse gas and is has 298 times the global warming potential of 1 kg of CO_2 equivalent (Hellebrand *et al.*, 2008). Uncertainties exist in estimates of N_2O emissions from managed soils due to a number of factors including; uncertainties related to the emission factors, natural variability, activity data, spatial aggregation, and lack of information on specific on-farm practices (IPPC, 2006). In this study N_2O formation is estimated to be 1.25% of available nitrogen from synthetic sources after ammonia volatilisation. This estimation is consistent with those used in published literature (Heller *et al.*, 2003, IPPC, 2006, Jørgensen *et al.*, 1997). As emissions factors for both synthetic fertilizer and biosolids are similar, N_2O emission rates for both are assumed to be the same according to the Biosolids Emissions Assessment Model (BEAM) (Brown *et al.*, 2010).

During the nitrification process in soils, nitrogen oxides (NO_x) may be produced in parallel with N_2O. NO_x emissions in this study for both synthetic and biosolid fertilizers are estimated according to Nemecek, Kägi et al. (2007).

Nitrate leaching under willow plantations is low in comparison with conventional agricultural crops (Dimitriou *et al.*, 2011). However, the loss of nitrates in the soil to groundwater can occur due to the fact that nitrate is easily dissolved in water. The addition of fertilizer to the soil, coupled with high rainfall rates in Ireland result in a high risk of leaching to groundwater. The nitrate leaching rate is estimated according to IPPC data (IPPC, 2006), it is assumed that 30% of applied nitrogen in both synthetic and biosolid fertilizers is lost in leaching to groundwater while 0.75% is converted to N_2O.

2.2.4 Harvest

Harvest losses represent an important loss during the conversion of the standing yield of the crop to the harvested yield. Harvest efficiency for was assumed to be 90% according to Styles and Jones (2008). The harvest loss was assumed to be the same for both direct chipping system and the rod harvesting followed by chipping system.

The yield from the first harvest is assumed to be 23 tonnes dry matter (DM) per hectare. In subsequent rotations this yield rises to approximately 30 tonnes DM per ha (Teagasc, 2010). Edenderry power plant, the assumed end user in this study, require the willow to be chipped and directly transported to the power plant, therefore no drying occurs. The willow yield on a wet basis (55% moisture content) is assumed to be 51 tonnes per hectare in the first rotation, rising to 67 tonnes per hectare in subsequent rotations. The lower heating value of the willow at this moisture level is approximately 7 GJ/t, on a dry matter basis this is 18.4 GJ/t (Caslin, 2010). The bulk density of chipped willow at 55% moisture content is assumed to be 285 kg/m^3 (Garstang *et al.*, 2002).

Two harvesting technologies are considered; direct chipping, and rod harvesting followed by chipping in the farm yard. It is assumed that the harvested willow chip and rods are transported an initial distance of 5 km from the field to the farm yard by tractor trailer. The willow rods are chipped in the farm yard before transportation.

Table 4 – Harvester productivity and fuel consumption

Harvest type	Productivity (ha/h)	Fuel consumption (l/ha)
Whole rod harvesting[a]	0.2-0.5	50
Direct chip harvesting[a]	0.1-1	100

[a](Association d'Initiatives Locales pour l'Energie at l'Environnement, 2007)

Data on the chipper was obtained from the ecoinvent database (Werner *et al.*, 2007) and was modified using data from Spinelli (2011). The productivity of the chipper was assumed to be 27.4 tonnes per hour with an associated fuel consumption of 1.68 litres per tonne.

2.2.5 Transport

The produced willow chip is subsequently transport 50 km by a 44 tonne (design gross vehicle weight) truck to the end user. The sensitivity analysis explores the effect of transporting 50 km by tractor and increasing the truck transport distance to 100 km. It is assumed that there is a 2% by mass loss during transport.

Data used in calculating the environmental impact of transport vehicles comes from the ecoinvent database (Spielmann *et al.*, 2007).

2.2.6 Carbon sequestration

Soil carbon sequestration occurs when plants remove CO_2 from the atmosphere through photosynthesis and incorporate into the soil carbon pool. Willow, as a perennial crop, has a high capacity to sequester carbon from atmosphere as it has a deep rooting system, causes minimal soil disturbance during its growing season and allows the accumulation of soil carbon over its long lifetime (approximately 22 years). The soil organic carbon is added to the soil by two mechanisms; decay of plant material on the surface and by root growth and senescence below the soil surface (Lemus & Lal, 2005). Factors affecting the rate of soil carbon sequestration under willow crops include; carbon inputs (net primary production), decomposition rates of the major soil carbon pools, initial soil carbon content (an inverse relationship with rates of soil carbon sequestration), crop/plantation management, and depth of soil being influenced by the bioenergy crop (Grogan & Matthews, 2002). The amount of carbon sequestered by SRC willow can be further enhanced if plantations are used for the bioremediation of effluents and sludges (Brown *et al.*, 2010).

The conversion of land from arable cropping to perennial bioenergy crops may result in greenhouse gas mitigation due to a number of factors including; reduced fertiliser inputs, increased CO_2 sequestration into root biomass and the soil, reduced fieldwork operations and ploughing, and other inputs associated with cultivation (ploughing, liming, herbicides, fuel usage, grain drying, etc) (Lanigan & Finnan, 2010). The magnitude of any greenhouse gas mitigation benefit depends strongly on the previous land use and former carbon stock levels (Don et al., 2012).

With the displacement of arable cropping with perennial willow cultivation, there will be a net increase in carbon sequestration. Arable crop lands have been shown to be net emitters of CO_2, mainly due to carbon loss in arable systems caused by ploughing and extended fallow periods, in comparison (Lanigan & Finnan, 2010). It has been estimated that carbon input into the soil associated with the conversion of arable land to willow increases by between 1.8–2.7 tCO_2 /ha/yr (Rowe et al., 2009).

Conversely, the conversion of grassland to willow cultivation is broadly considered to have no impact on long-term net carbon sequestration (Lanigan & Finnan, 2010, Rowe et al., 2009).

Total site preparation losses (ploughing and soil preparation) are assumed to be 1 tCO_2/ha, according to Lanigan (2010). It is assumed that no net carbon sequestration occurs as the reference land use is grassland.

2.3 Life Cycle Impact Assessment

The attributional LCA for willow cultivation in this case was carried out using CML 2001 (Guinée *et al.*, 2002) and ecoinvent methods (Frischknecht *et al.*, 2007). The impacts assessed include acidification potential (AP), eutrophication potential (EP), and global warming potential (GWP). The cumulative energy demand (CED) is also evaluated, allowing the energy ratio (energy out versus energy in) of the system to be calculated.

2.3.1 Global warming potential

Global warming potential (GWP) is an important environmental impact to consider in the evaluation of renewable energy systems. GWP refers to the potential of the system to trap greenhouse gases in the atmosphere, leading to climate change. Gases which contribute to global warming include carbon dioxide, methane and nitrous oxide. GWP is expressed in kg CO_2-equivalents (Guinée *et al.*, 2002).

2.3.2 Acidification potential

Acidification potential (AP) is an important environmental impact to consider when evaluating bioenergy systems as it is expected to increase with increased production of biomass. AP is caused by the emission of acids or acid forming substance the environment, resulting in acidification of soil and water. Acidification harms natural life such as fish and trees, and also causes damage to buildings etc. The main sources for emissions of acidifying substances are agriculture and fossil fuel combustion. Examples of contributing substances include; sulphur dioxide, nitrogen oxides and ammonia. AP is expressed in kg SO_2-equivalents (Guinée *et al.*, 2002).

2.3.3 Eutrophication potential

Eutrophication potential (EP) is another environmental impact important in evaluation bioenergy systems. EP is defined as the potential of nutrients to cause over-fertilisation of water and soil which in turn can result in increased growth of undesirable biomass. This biomass has negative impacts on other life in the ecosystem. Contributing substances include; phosphates, nitrates, ammonia, nitrogen oxides etc. EP is expressed in kg PO_4-equivalents (Guinée *et al.*, 2002).

2.3.4 Energy demand and energy ratio

Cumulative energy demand (CED) of a product or system characterises both the direct and indirect energy use throughout the life cycle. It is a particularly important evaluation of bioenergy systems in order to ensure that more energy is not consumed than produced. CED is expressed in mega joules (MJ).

In addition, Huijbregts et al. (2005) found that CED correlates well with most environmental life cycle impact categories and can be considered an appropriate proxy indicator for environmental performance.

A further way to assess advantages of renewable energy systems may be to evaluate the pure energy ratio of the system. The term "energy ratio" is used to characterize relations between the energy input and output. Energy ratio is a ratio between the energy output and energy input (Klvac, 2011).

2.3.5 Comparison with fossil fuels

When evaluating any bioenergy system it is important the environmental impacts be compared with fossil energy reference systems (Schlamadinger *et al.*, 1997). In this study, the production of willow biomass is compared to the provision of coal and peat, fuels with which willow is commonly co-fired. Data on the environmental impacts of coal and peat supply were obtained from the ecoinvent database (Dones *et al.*, 2007).

3 Results

Table 5 quantifies the impacts associated with the production of 1 GJ of energy embodied in the harvested willow chips. Table 4 gives the results of scenario 1 which is considered to be the reference scenario in this study; willow chip production using synthetic fertiliser, direct chip harvesting and transporting the product 50 km by truck to the end user. In this scenario, the production of 1 GJ of willow chip requires 59.7 MJ of energy, and results in the emission of 5.84 kg CO_2-eq, 0.0336 kg SO_2-eq and 0.0092 kg PO_4-eq.

Table 5 - LCA results per GJ of energy contained in willow chip biomass for the base-case scenario

Impact category	Unit	Land Preparation	Planting	Cutback	Maintenance	Harvest	Crop Removal	Transport	Total
AP	kg SO2 eq	0.0005	0.0011	0.0001	0.0216	0.0058	0.0003	0.0043	0.0336
EP	kg PO4-eq	0.0002	0.0009	0.0000	0.0052	0.0017	0.0001	0.0011	0.0092
GWP	kg CO2 eq	0.43	0.15	0.01	2.99	1.32	0.05	0.88	5.84
CED	MJ	1.3	1.5	0.2	19.4	21.6	0.8	14.9	59.7

Figure 3 shows the percentage contribution of each of the life cycle stages to the overall impacts for each category for the reference scenario (direct chipping of willow grown using synthetic fertilizer and transported a distance of 50 km by truck).

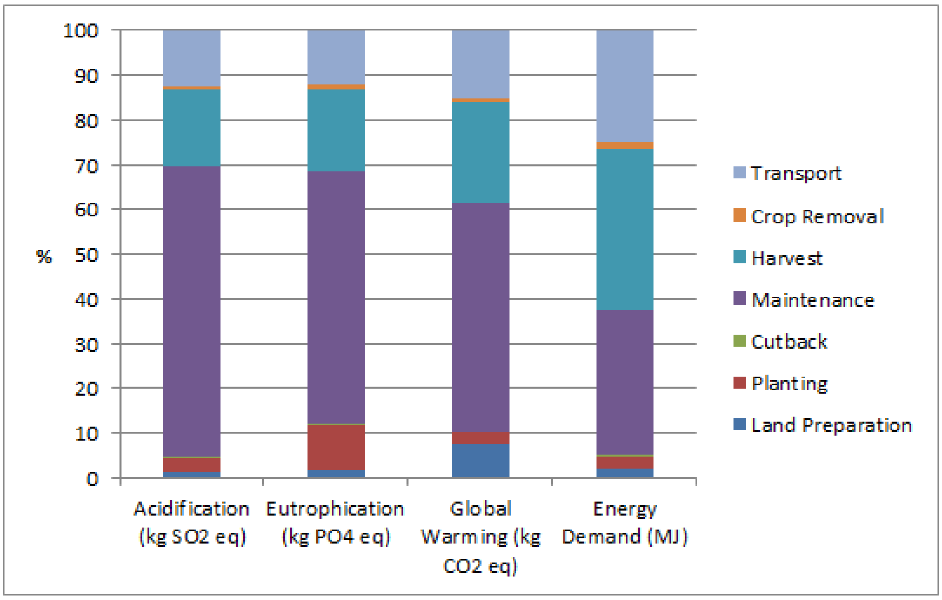

Figure 3 - Percentage contribution of life cycle stages to each impact category for the base-case scenario

The results clearly identify three important processes in the production chain; maintenance, harvest and transport. These three steps in the supply chain contribute the largest share of impacts to each of the impact categories. Maintenance, harvest, and transport, are repeated for every harvest cycle throughout the life cycle, while the other steps are only carried out once. Maintenance of the willow crop is highly energy intensive, with energy required for the manufacture of synthetic fertilizers but also in diesel consumption in the farm machinery used in fertilizer application. Willow harvesting and transport are also significant energy intensive processes with high consumption of diesel in the chipper harvester and truck engine respectively, contributing to the high energy demand.

3.1.1 Energy demand and energy ratio

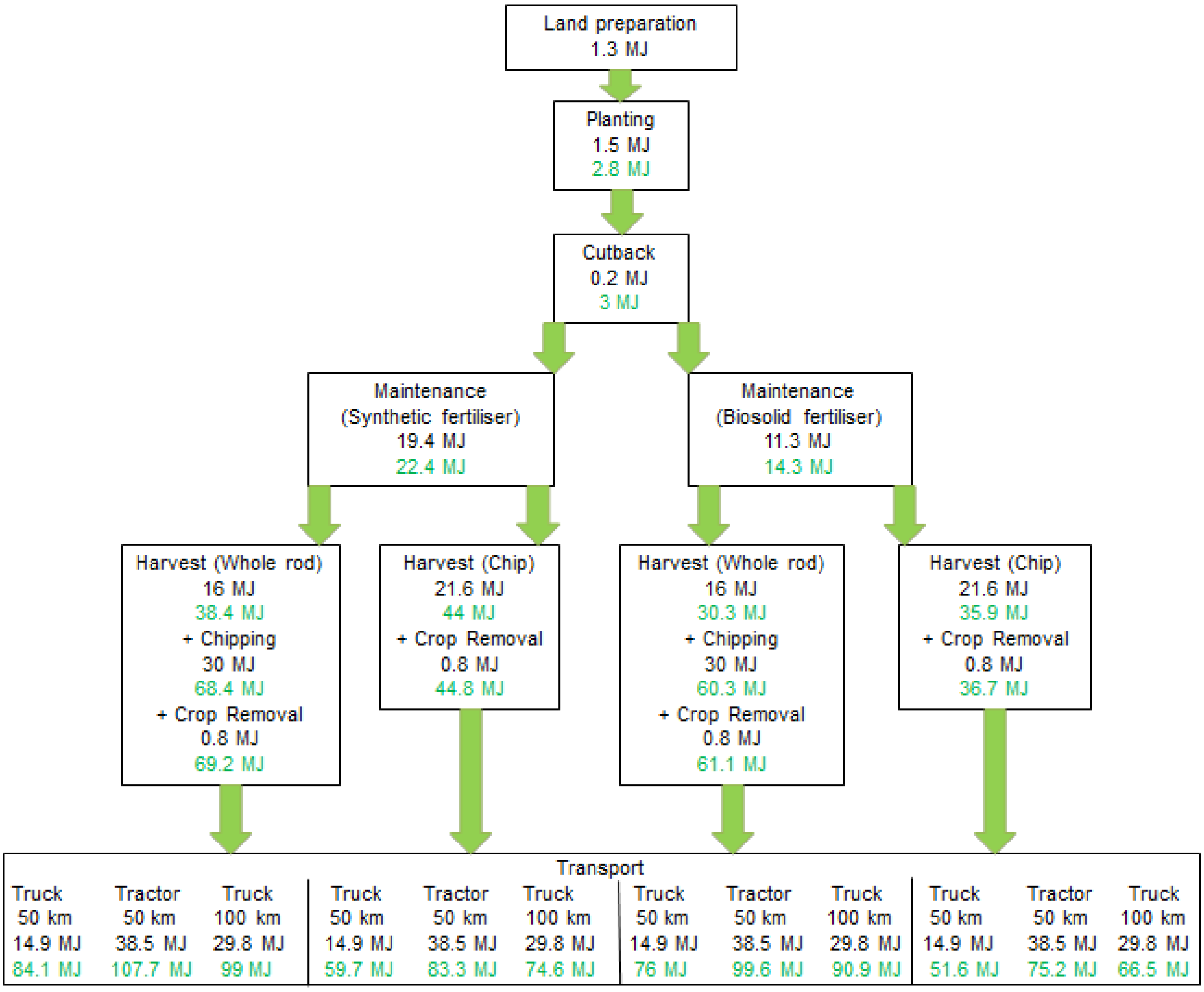

Figure 4 - Energy flow diagram (per GJ of willow chip produced)

Figure 4 demonstrates the energy requirements of each step in the life cycle. Figures in black indicate the energy demand associated with each individual step, while figures in green represent cumulative energy demand along the production chain. The final figures show that the cumulative energy required to produce 1 GJ of energy contained in the harvested willow. Energy consumption ranged from 51.6 – 107.7 MJ/GJ biomass, with biosolid application, direct chip harvesting, and biomass transportation 50 km by truck requiring the least energy input. On the other hand, the most energy intensive system involved synthetic fertiliser application, rod harvesting and tractor-trailer transport over a distance of 50 km.

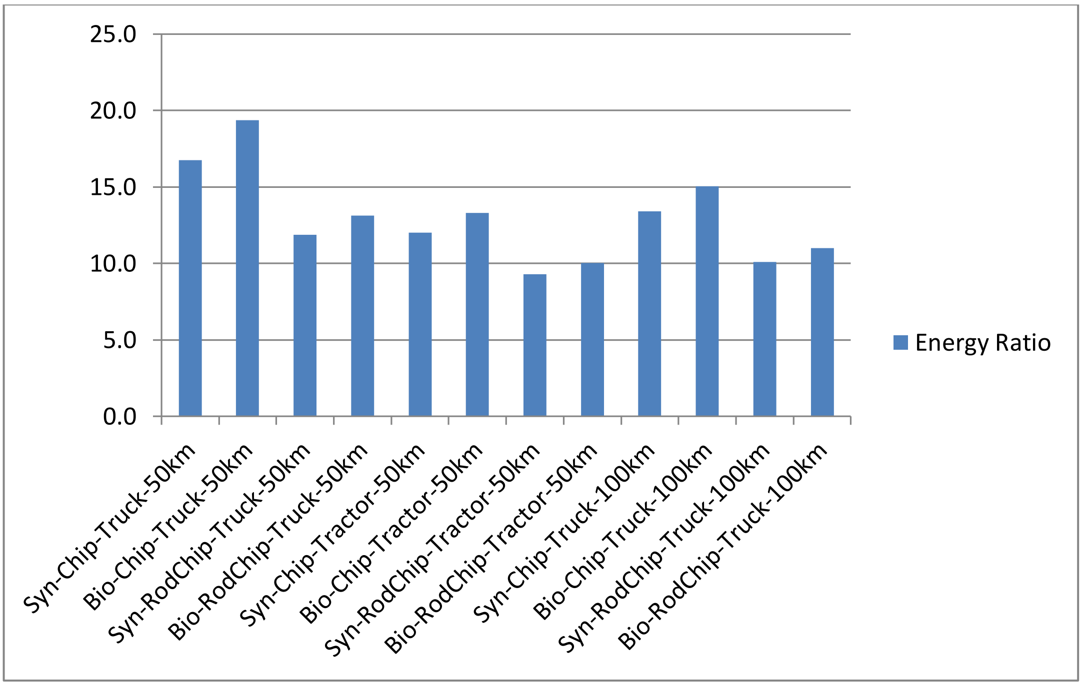

Figure 5 - Effect of management scenarios on energy ratio

Figure 5 graphs the energy ratio of the willow production system under the different management scenarios. The energy ratio ranges from 9.29 – 19.38.

3.1.2 Global warming potential

One of the major environmental benefits associated with bioenergy use is the reported greenhouse gas benefits. Greenhouse gas emissions from the reference scenario (willow chips, synthetic fertilizer and 50 km transport distance), amount to 5.84 kg CO_2-eq per GJ of energy produced. The manufacture of synthetic fertilizers is an energy intensive process, contributing to a large degree to the overall greenhouse gas emissions of the system. The effects of the different management scenarios on overall GHG emissions of the system are outlined in figure 6.

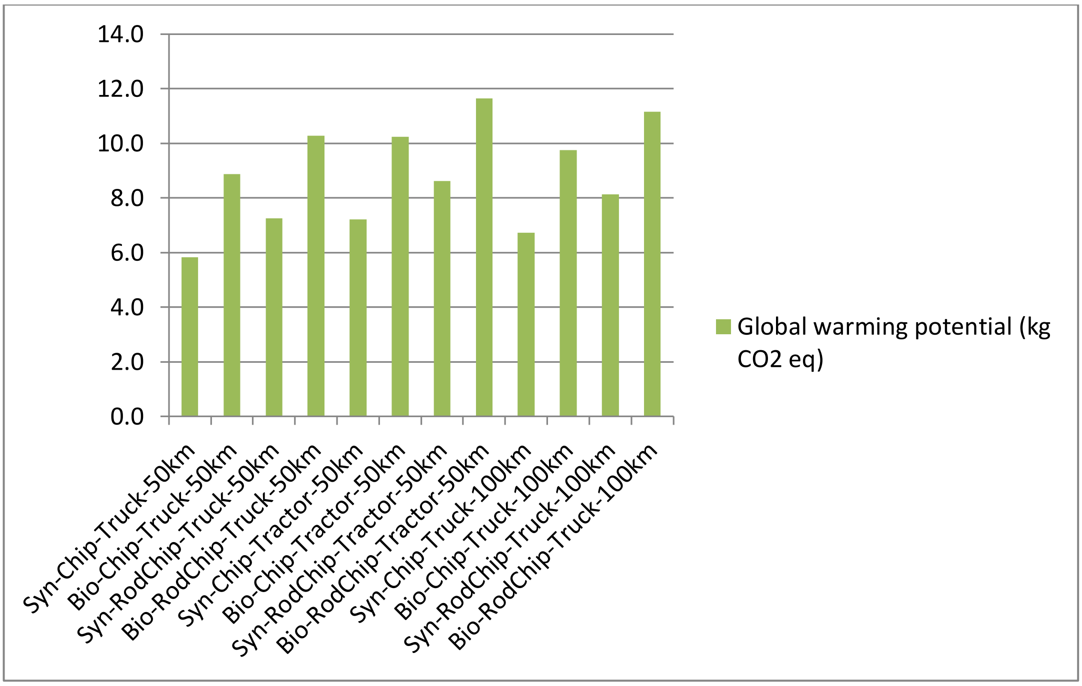

Figure 6 - Effect of management scenarios on GWP

3.1.3 Acidification potential

As can be seen from Figure 3, the major contributor to overall acidification potential of the system is maintenance of the energy crop. Acidifying emissions result from combustion of diesel in machinery used in field work operations. However, the majority of acidifying emissions result from emissions to the environment from the use of fertilizers.

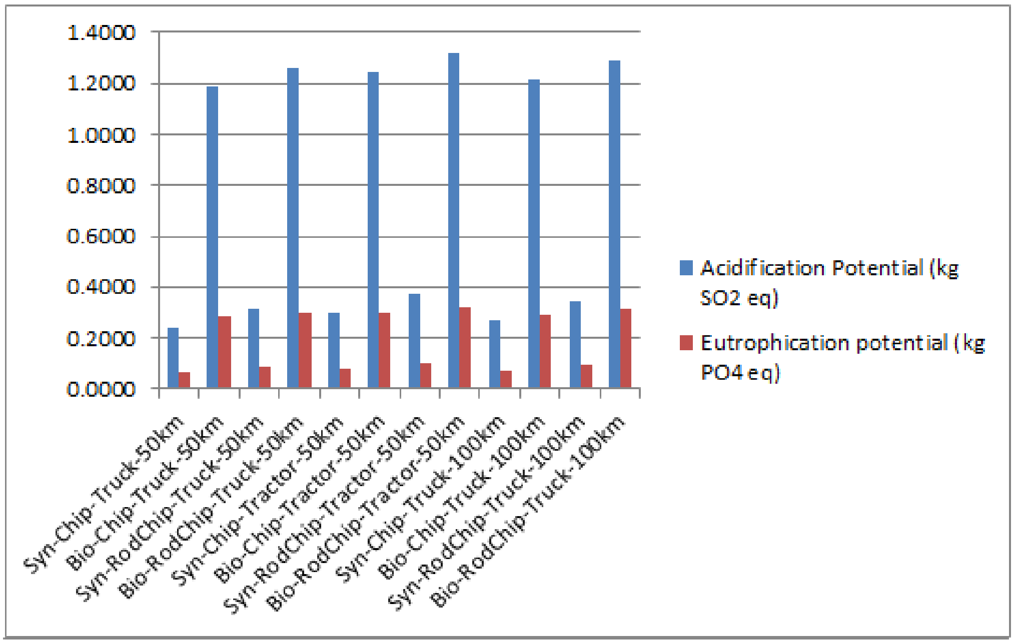

Figure 7 - Effect of management scenarios on AP and EP

3.1.4 Eutrophication potential

Figure 3 demonstrates that the maintenance of the willow crop results in the highest contribution to overall eutrophication potential. Furthermore, as shown in figure 7, the application of biosolid fertilizer also increases eutrophication potential due to increased ammonia volatilisation, however not to the same extent as acidification potential.

4 Discussion

The positive energy ratios displayed in figure 5 (9.29 – 19.38) highlight the strong energy performance of the system and are slightly higher than the 3 to 16 range for the cradle-to-plant assessments reported by Djomo et al. (2011). The energy ratios are lower than those reported by Dubuisson & Sintzoff (1998), as they include drying of the willow biomass. In addition, Heller et al. (2003) reported significantly higher energy ratios for willow production of approximately 33.2 – 83 depending on yield and fertiliser application rate. The ratio specified by Heller et al. (2003), assume drying of the biomass which increases the energy content of the material, hence increasing the energy ratio, they also fail to consider transport in these estimates. In this study, the harvested willow is assumed to have a lower energy content as the material is exported from the farm to the power plant directly after harvest, allowing no time for drying. Furthermore, the energy ratios of the willow scenarios in this study are lower than other reported values by Matthews (2001) and González-García et al. (2012b) as they do not consider transport in their analysis.

The range of global warming potential figures in this study (5.84 – 11.65 kg CO2-eq/GJ) are comparable to those reported by Dubuisson & Sintzoff (1998), but are all higher than those of 4.8 kg CO2-eq/GJ reported by Matthews (2001) as their analysis assumes lower fertilisation rates and includes only transport of 3.2 km to the farm.

4.1 *Alternative fertilisers*

The production of synthetic fertilisers contributes significantly to each of the impact categories studied due to the energy and resources used to produce them. GHG emissions from synthetic nitrogen fertilizers also originate from N_2O from the production process, and the technology utilized is an important factor in GHG emissions (Börjesson & Tufvesson, 2011). The application of biosolids to the crop as an alternative fertiliser has the potential to reduce these impacts through the utilisation of a waste product to meet the crops nutrient requirements. Biosolid fertilisation removes the need for synthetic fertilizers which require significant energy inputs in manufacture. Sensitivity analysis was carried out on substituting biosolids for synthetic fertilisers. Figure 7 shows that using biosolids in place of synthetic fertiliser increases both acidification and eutrophication potential by 259-404% and 136-182% respectively. This increase in acidifying emissions can be attributed to a 24% higher ammonia volatilisation rate associated with the use of biosolids when compared to synthetic fertilizer use. Furthermore, as presented in figure 7, the application of biosolid fertilizer also increases eutrophication potential due to increased ammonia volatilisation, however not to the same extent as acidification potential. These findings echo Gilbert et al. (2011) who also found that higher emissions result from a higher proportion of the inorganic content volatilising shortly after spreading onto the land. In addition, global warming potential increases by 35-52% when utilising biological fertiliser. The increase in global warming potential is due to the emission of CO_2 during anaerobic digestion which is part of the pre-treatment process in this study. However, utilising biological fertiliser positively affects the cumulative energy demand, reducing it by 8-14%, and thereby increasing the energy ratio of the biosolid scenarios.

4.2 Harvesting

The use of different harvesters has a significant effect on energy demand and emissions. An analysis of the energy flow diagram (figure 4), which shows each of the different processing steps in the scenarios, highlights that although energy consumption in the rod harvester is lower than the direct chipper, this energy saving is significantly outweighed by the energy required to subsequently chip the rods. Rod harvesting increases the energy demand by 29-47%. In addition, the overall energy ratio for rod harvesting is significantly lower than when direct chipping is employed. The use of the rod harvester subsequently results in increases in AP of 6-32%, EP 7-33%, and GWP 14-24%. An advantage of rod harvesting is that storage and drying is easier as air flow between the rods is less restricted than through chips. The drying of the rods will result in a higher calorific value than wet chip. However, as drying does not occur in the particular supply chain in this study, the drying benefits of rod harvesting benefits are not included in the results.

4.3 Transport

The lowest impacts from transportation occur when the biomass is transported 50 km by truck. Truck transport over a distance of 100 km increases AP by 2-13%, EP by 3-12%, by GWP 9-15%, and CED by 18-29%. Tractor-trailer transport over a distance of 50 km increases AP by 4-24%, EP by 6-29%, GWP by 13-23%, and CED by 28-46%. As such, tractor-trailer transportation over a distance of 50 km causes greater environmental impacts than transporting the biomass by truck over a greater distance of 100 km. This shows that there is a higher impact transporting biomass short distances using agricultural machinery and tractors, compared to the lesser impact of long distance transport by dedicated haulage equipment. This echoes the finding by Thornley (2008) that lorry transport makes a minor contribution to overall emissions while tractor transport emissions are more significant.

4.4 Comparison with fossil fuels

The energy ratios of all willow chip scenarios are higher than both coal and peat which have an energy ratio of 2 and 5 respectively (Dones *et al.*, 2007), implying that more energy is required to produce these fuels.

Greenhouse gas emissions associated with willow production in all scenarios are lower than coal supply which emits approximately 12.28 kg CO2 eq per GJ of coal (Dones *et al.*, 2007). GWP of peat provision is lower than the production of willow, as the harvesting of peat is the only process considered. Although combustion is outside the scope of this analysis, further GHG reductions would occur when comparing biomass combustion to fossil fuel combustion. The CO_2 released during biomass combustion is approximately equal to the CO_2 the biomass had accumulated from the atmosphere during its growing cycle, this convention is widely adopted in LCA studies of biomass-to-energy systems (Cherubini *et al.*, 2011).

When compared to conventional fossil fuels, coal and peat, the willow biomass system performs favourably in terms of acidification and eutrophication potentials.

5 Conclusion

The results of this study highlight the positive environmental benefits of short rotation coppice willow production. The results identify three key processes in the production chain which contribute most significantly to all impact categories considered; maintenance, harvest and transportation of the crop. Sensitivity analysis on the type of fertilizers used, harvesting technologies and transport distances highlights the effects of these management techniques on overall system performance. 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 considered. These results highlight positive and negative effects of using biosolids that would need to be weighted and considered in forming a conclusion on whether to apply biosolids or synthetic fertilizer. Additionally, a crucial aspect in the environmental performance of fertilizers is the design and technology of the production system. Rod harvesting compares unfavourably in comparison with direct chip harvesting in each of the impact categories considered due to the additional chipping step required. The results show that dedicated truck transport is preferable to tractor-trailer transport in terms of energy demand and environmental impacts. This finding highlights the importance of keeping biomass supply and use on a regional level, in order to keep transport distances low and thus maximise the environmental benefits attributable to biomass. Finally, willow chip production compares favourably with coal provision in terms of energy ratio and global warming potential, while achieving a higher energy ratio then peat provision but also a higher global warming potential. In this study only emissions from the production of the willow chip are included, end-use emissions from combustion are not considered.

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Figure 1: Area of willow planted under the bioenergy scheme until 2010 (Dillon, 2011)

Figure 2: System boundary of willow cultivation. Dotted lines denote material inputs to the system.

Table 1: Willow production scenarios

Table 2: Summary of field operations and associated machinery data

Table 3: Data summary of inputs to cropping system (Teagasc, 2010)

Table 4: Harvester productivity and fuel consumption

Figure 3: Percentage contribution of life cycle stages to each impact category for the base-case scenario

Table 5: LCA results – AP, EP, GWP, CED per GJ of energy contained in willow chip biomass for the base-case scenario

Figure 4: Energy flow diagram.

Figure 5: Effect of management scenarios on energy ratio

Figure 6: Effect of management scenarios on GWP

Figure 7: Effect of management scenarios on AP and EP