Life Cycle Assessment of Jerusalem artichoke (Helianthus tuberosus): *a New Zealand 'Cradle to Farm Gate' assessment of net energy yield, global warming potential and eutrophication impacts of biomass crop production for bioenergy*

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Funded by the Biomass to Syngas to Liquid Biofuel project, Chemical and Process Engineering Department, University of Canterbury

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Summary

The production of biofuels from crop biomass is one means to address two key issues: finite fossil fuel supply and environmental impacts of fossil fuel use on climate change through global warming. This Life Cycle Assessment (LCA) report is one aspect of a New Zealand (NZ) biofuels research project at the University of Canterbury to advance biomass gasification and liquid fuel synthesis from the syngas. The aim is to characterise the three most promising non-woody biomass species for use as gasification feedstock. A protocol was developed for each species to act as a blueprint to grow the crop under NZ conditions. The species reported here is Jerusalem artichoke (*Helianthus tuberosus*). It looks like the related species, sunflower, but is usually grown for its tubers. The plant tops are of interest in their own right, having high biomass production of up to 30 tonnes dry mass per hectare (tDM/ha).

One element of characterising each species and developing its protocol was to carry out an LCA to quantify environmental impacts and energy consumption from producing the biomass feedstock. The scope of this study is from Cradle to Farm Gate, not to the final manufacture and use of fuel. LCA methodology was followed, with identified limitations and a modified presentation style. LCA practice recognises several environmental impact categories; this study quantified two factors, Global Warming Potential (GWP) and eutrophication (EUT). Energy consumption and net energy yield (gross energy stored in the biomass minus energy consumption) were also calculated, as they are of high relevance to a project designed to introduce a new fuel energy technology.

The main task was to develop a Life Cycle Inventory (LCI) containing the most appropriate inputs for calculating the impacts of each farming operation in Jerusalem artichoke (JA) biomass production in NZ. A spreadsheet approach was used for this. This alternative to the use of LCI databases was feasible given the practical decision to limit the LCA to two impact categories. The LCI was best developed on per ha basis, since that is how farming inputs are quantified. The basic functional unit (FU) used to examine (and in the future to minimise) JA production impacts on both an area basis and time basis is: FU = *cultivation of 1.0 hectare of Jerusalem artichoke for shoot biomass during the year of planting*. Environmental impacts will differ in a long-lived JA planting, which is a management option due to self-replacement of plants from previous years' tubers, as will be discussed.

The overall impacts to plant and grow a first year JA planting were energy consumption of 12.9 GJ/ha-yr and GWP of 1366 kg CO_2e/ha-yr. Fertiliser use was the primary hotspot for both. It contributed 63% of total energy consumption. More of the fertiliser impact on GWP was from the soil emissions of N_2O and CO_2 (564 kg CO_2e/ha-yr from N fertiliser alone) than fertiliser manufacture (357 kg CO_2e/ha-yr) and the two impacts together were 70% of GWP.

Diesel fuel use to grow JA, while greater than for the biomass crop giant miscanthus, was quite secondary in terms of both its energy consumption and GWP impact. In a perennial planting of JA the annualised energy use is estimated to be 8.56 GJ/ha-yr, since nearly all operations other than fertilising and harvesting can be omitted; it may be < 7 GJ/ha-yr if the fertiliser rate can be reduced compared to the rates used in this LCA for a first year planting.

A significant reduction in NZ GWP due to GHG emissions from fuel use by farming and transport could result from substituting fossil diesel with biodiesel. The most direct way to measure the benefits of substitution is to determine the GWP footprint of producing and using the biodiesel and subtract that from the GWP footprint (12.4 t CO_2e/ha) from combusting the fossil diesel it replaces. The GWP footprint from processing JA biomass to biodiesel has not been measured, but an illustrative calculation was made from literature values and added to the Cradle to Farm Gate GWP. The calculated fuel-substitution benefit is 10 t CO_2e/ha, which is between 4 and 40 times the full Cradle to Grave GWP footprint for JA, depending on how conservatively the GWP footprint of processing biomass into biodiesel was calculated.

Carbon sequestration in the soil under a JA crop may also be an important factor in compensating for the GWP due to soil emissions caused by N fertiliser. While this has not been researched, there is reason to hypothesise that the total gain in SOC could be as great as that of the better-studied Mxg crop.

EUT, which lowers the quality of waterways, is the second impact category studied (in units of phosphate equivalent and focusing on emissions from fertiliser and diesel fuel use). The overall first year EUT footprint from JA cropping is 2.74 kg PO_4e/ha-yr. EUT impacts from N-containing emissions were nearly all from the use of fertiliser nitrogen (1.97 kg PO_4e/ha-yr). The other EUT source is phosphorus (P) fertiliser, attached to soil that is eroded to waterways. The crop removal of P in JA shoots at autumn is likely to range from 10-20 kg/ha-yr in a 25 tDM/ha crop. This is considerably higher than for the miscanthus species Mxg, but less than half of the uptake by the cereal species triticale. The highest likely rate of P fertiliser use (23 kg/ha) will have an impact on EUT of 0.77 kg PO_4e/ha-yr (this would be smaller in subsequent years of a perennial JA plantation, as P is not required annually).

Net energy yield equals the gross energy yield (455 GJ/ha-yr) minus energy consumption (12.9 GJ/ha-yr) or 442 GJ/ha-yr. The energy ratio between gross yield and consumption is 35 to 1 in the planting year and about 50 to 1 in following years. This LCA suggests there is scope for reduction in energy consumption in JA farming operations (such as by reducing N fertiliser use).

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INTRODUCTION

Research to develop new transport fuels has two aims. The first is to address the issue of finite fossil fuel supply. Secondly, new biofuels could reduce the key environmental impact of fossil fuel use, namely climate change through global warming. To assess this however, it is also important to know what the environmental effects of each biofuel are. Life Cycle Assessment is the formal tool used to provide this information. To quote a recent LCA in New Zealand (McDevitt & Sneadon, 2011): "Life Cycle Assessment generally comprises four major components:

- Goal and Scope definition;
- Life Cycle Inventory - data collection and calculation of an inventory of materials, energy and emissions related to the system being studied;
- Life Cycle Impact Assessment - analysis of data to evaluate contributions to various environmental impact categories; and
- Interpretation - where data are analysed in the context of the methodology, scope and study goals and where the quality of any study conclusions is assessed".

While this structure was followed for this environmental assessment of Mxg biomass production, it is not intended to be a complete LCA document as prescribed by the body of New Zealand LCA professionals. Rather, it aims to serve the needs of a particular biofuels research project by the Chemical and Process Engineering Department of the University of Canterbury (U of C). The project is advancing the technology of biomass gasification and liquid fuel synthesis from the syngas and is named Biomass To Syngas to Liquids (BTSL).

One project aim is to characterise the best non-woody biomass species for use as gasification plant feedstock. This research aspect has been provided by Rocky Renquist, the principal of a subcontract with the University of Canterbury. The work was done first within the NZ Institute for Plant & Food Research, and then with Bioenergy Cropping Solutions Ltd.

The findings from a Life Cycle Assessment will be a valuable element in the overall project so that the environmental impacts of producing and using the end product biofuel are known and especially to quantify the energy balance of the overall process, since the underlying aim of the technology is to produce an energy source for transport. Milestone 28 under Objective 4 of the U of C contract with MBIE reads: "Life cycle analysis is conducted to analyse the energy use and environmental impacts during biomass production and handling."

Many species were investigated and screened in field trials and three species were selected. Milestone 28 under Objective 4 of the U of C contract with MBIE required that a protocol be developed for each of these final species, and in relation to that: "Life cycle analysis is conducted to analyse the energy use and environmental impacts during biomass production and handling." The practical intent of using LCA is to see how successful each species would be as a sustainable gasification feedstock, also enabling a comparison of the biomass species.

The species assessed in this LCA is Jerusalem artichoke (*Helianthus tuberosus*) a perennial type crop with high biomass production, greater than 25 tDM/ha. It also is reported to use relatively low farming inputs (with presumably low environmental impacts), but these claims need to be quantified under NZ conditions. These features make it a strong candidate for biomass production.

This study of JA will analyse the energy use and two major environmental impacts during biomass production and handling using LCA methodology. LCA has been applied to each of the three most promising biomass species for NZ; each of these also had a Protocol written to document how best to grow and handle the biomass. The practical intent of using LCA is to make the Protocol for each species more robust by quantifying how sustainable it is as a gasification feedstock with respect to the impact factors studied. It also enables a comparison of environmental footprints among the three biomass species from Cradle to Farm Gate.

What is not part of the Cradle to Farm Gate LCA, but has the potential to give a large reduction in GWP, is the use of biofuel for the tractor and truck operations used to produce the biomass from which the biofuel is produced. This will be considered further in the DISCUSSION section (under the subheading GWP benefit of fossil fuel substitution with JA biofuel).

METHODS

Our New Zealand field trials with Mxg were carried out over five years, primarily in the Hawke's Bay region. Full details are described in "Jerusalem artichoke Protocol" from Bioenergy Cropping Solutions Ltd to the BTSL Project. Relevant details to this LCA work are included here under METHODS and relevant field trial findings are part of the RESULTS section of the LCA. Given the lack of commercial crop data, the use of these site specific data and research findings ensures a more realistic assessment for this "new to NZ" crop species, especially with regards to variables such as yield and fertiliser inputs.

The LCA has a regional Hawke's Bay focus as field trials were performed there. Since plant growth is climate dependent, the soil and crop data from Hawke's Bay should not be applied directly to biomass production in other NZ regions. However, since a previous modelling study (Kerckhoffs et al, 2012) quantified the total area of relevant biomass production sites and generated maps of NZ showing these, it will be possible to extrapolate (in a qualitative way) findings from Hawke's Bay to the mapped 'summer dry' marginal sites in other parts of NZ (see DISCUSSION section).

An LCA approach was chosen that met the time/resource constraints and the need to be accurate for applying to New Zealand cropping of biomass species. The agricultural inputs for crop production available in NZ were to some degree present in research papers that relied on Life Cycle Inventory data (largely published in Europe) and were identified as relevant by LCA professionals in NZ, with some modification to suit NZ conditions. When European LC inventory data are directly applicable they are most efficiently accessed through LCA software designed for this purpose (Baumann & Tillman, 2004).

Another way to develop these LCI data is by constructing an operational calculation worksheet created for this purpose. This is the primary approach used in the current analysis given the practical decision to limit the LCA to two environmental impact factors, as appropriate for the purpose and time resources available. The spreadsheet approach also allowed expert involvement in the selection of the inventory data, ensuring they were deemed the most appropriate for use in NZ crop production. A few of the LCI data were obtained from LCI databases such as Ecoinvent (ref), sourced through the BTSL project collaborators who carried out the Farm Gate to Grave study.

Energy consumption and net energy yield (gross energy stored in the biomass minus the energy consumption inputs) are clearly of high relevance to a project designed to introduce a new fuel energy technology. In addition, the two environmental impact factors global warming potential (GWP) and eutrophication (EUT) were chosen for the biomass species assessment. GWP is the impact factor of most direct relevance to assessment of a technology designed to replace the fossil fuels diesel and petrol that are key contributor to greenhouse gas (GHG) emissions. Adverse agricultural impacts on the environment are most noticeable with regard to the pollution of surface and ground water. The LCA impact factor most likely to show measurable water quality effects of this type is EUT. The footprint for these three aspects (energy consumption, GWP and EUT) were quantified in this LCA.

Goal of the study

The goal of this LCA study is to assess the impacts of growing Jerusalem artichoke (JA) in NZ on energy consumption and two impact factors, GWP and EUT. The LCA will develop an inventory of materials, energy input, emissions and biomass output related to the Mxg farming system. This will use new NZ data sets, appropriate international data and calculations using those data.

The *functional unit* (FU) of the study is a measure that reflects the usefulness (where appropriate and available) of a system in comparison to other systems. This LCA is focused on the cradle to farm gate impact. Since a JA plantation may grow well for several years and its duration has not been determined in NZ, the focus chosen for this study is the first year of a new JA planting. As a result, the impacts that will be quantified will represent a ‘worst case scenario’ for JA, grown as an annual crop.

Therefore, the functional unit used to examine (and in the future to minimise) JA production impacts on both an area basis and time basis is: *FU = cultivation of* one *hectare of JA shoot biomass during the year of planting*. Another reason to use this functional unit is practicality: farming inputs are quantified on a “per ha” basis. The reference flow for this LCA is therefore 1ha of land.

The JA biomass yield is set at a realistic value and the overall environmental impact of producing the biomass (on an area basis) is not greatly influenced by the yield.

Finally, from the perspective of producing energy from a range of crop species, a different FU is required, because other biomass crops do not necessarily have the same dry mass yield per ha. Therefore, our final results will also be presented for FU = *1 ton of dry biomass (contained within biomass of known moisture content, at the farm gate).* This second FU is the best future basis for comparing impacts to the farm gate as part of the overall cycle of producing biodiesel.

The target audience of the study will be the BTSL research project at the University of Canterbury that has contracted the work, and later the public readership of the reported findings of the BTSL project. This LCA is not intended to be used to support comparative assertions intended for public disclosure.

Scope of the study

This is a 'cradle to farm gate' study. It covers environmental impacts from all JA production steps: raw materials extraction for use in farming equipment and activities (the cradle), operations to grow the biomass, biomass harvesting and its transport within-farm from the field to the farm gate (as a proportional part of transport to the processing plant). In order to quantify the net energy yield, data from the above steps include the relevant direct primary energy in fuel used to operate machinery for operations from soil cultivation to harvest and transport to the farm gate and indirect energy embodied in machinery and agrichemical inputs.

Two key environmental impact factors will be characterised, and emissions that relate to global warming potential (GWP) and eutrophication (EUT) will be quantified. This will enable comparisons with the other New Zealand-grown feedstocks chosen to supply a future gasification plant.

The geographic scope of the study, in terms of energy output in the Mxg crop biomass and crop environmental responses, is for the region of Hawke's Bay in the North Island of NZ. Most data were from a large trial in a deep fine-textured soil with subsurface soil water, with supplemental data from a larger trial in a shallow coarse volcanic soil over subsoil of river stone gravel. More details of the NZ field trials are given in the Life Cycle Inventory subsection. Commercial JA plantings in NZ are only beginning, so there was no opportunity to collect farm data as a basis for LCI inputs.

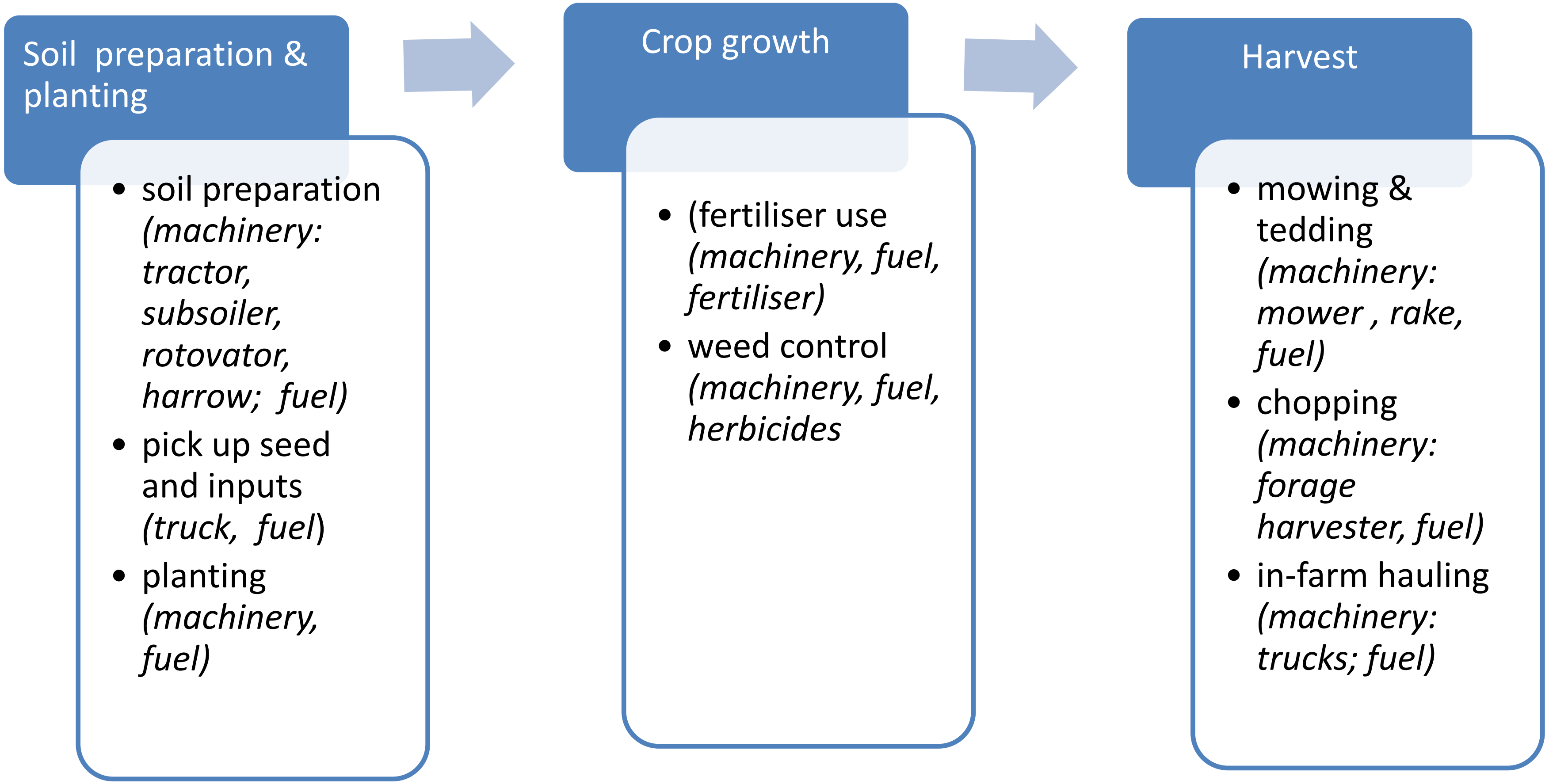
The reference year (with associated Hawke's Bay weather) for the present study is 2012.

The system boundary from this study is detailed in Figure 1. While the system is quite inclusive, cut-off decisions were made to exclude the emissions from employees in the supply chain and also manufacturing & maintenance inputs for tractor implements (the tractors themselves are included).

No allocation is required in a perennial JA planting as whole shoots are put to a single use and tubers are left in the ground. This could change if a market develops for the tubers as a food crop, with tuber harvest causing the JA crop to be grown as an annual. Allocation of environmental impacts in that case would be >50% to the food products, with shoot biomass for fuel treated more as a crop residue. This LCA is taking only the first approach, with no allocation.

The system boundary from this study is detailed in Figure 1. While the system is quite inclusive, cut-off decisions were made to exclude the emissions from employees in the supply chain and also manufacturing & maintenance inputs for tractor implements (the tractors themselves are included).

Figure 1. Flow diagram – Jerusalem artichoke farming operations. The crop production stages are in the dark background boxes, the activities in the front boxes and inputs in parentheses and italics.



Life Cycle Inventory (LCI)

The aim of this LCA is to identify the most appropriate LCI input values to assess JA production of biomass in NZ conditions. Usually, LCA practitioners rely on LCA software, such as Gabi (developed by PE international Ltd). These software packages include databases such as Ecoinvent, and perform calculations automatically using the chosen data from the inventory. However, the cost associated with such software and the training required to be an efficient user are prohibitive for the current project. Therefore, we developed our own calculation spreadsheet using MS Excel, as noted near the start of this METHODS section, to perform the same calculations. The only difference is that all input data and conversion factors have to be entered manually, rather than selected from a database. The name given to the calculation spreadsheet used this report is the Operations Calculation Sheet. Detailed descriptions of the LCI section are given below.

The first subsection in this LCI section is on the inputs to the inventory that characterise the operations required to grow miscanthus biomass, from Cradle to Farm Gate. The next subsection describes the structure of the Operational Calculation Sheet; populating it with appropriate values constituted the principal task of the LCI process.

Data collection for the JA field experiments began in 2010 and for the LC inventory it began during mid-2013. This procedure inventories inputs to and outputs from a JA biomass production system. These LCI data were quantified and expressed relative to the primary functional unit (*FU = cultivation of one hectare of JA shoot biomass during the year of planting*). Therefore units for the data are expressed per ha. These were initially developed from intermediate units, such as impacts per kg of fertiliser used.

A literature review had already identified several papers on LCA of biofuels and biomass crops for use in bioenergy generation. While there were large enough differences between studies in the calculated values for energy balance and environmental impacts to be wary of accepting without question the values from any one study, there was an adequate general pattern of results to guide a decision on which impact factors should be prioritised in this study. It was necessary to focus on only a small number of factors due to limited time and other resources.

Crop management factors in the spreadsheet were obtained in part from NZ information on other related species, since JA has not been grown commercially. Input factors were derived in many cases, however, from published JA research and crop management reports in Europe and the USA. Some of these inputs were able to be refined for use in NZ once the Mxg field trial results were assessed.

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LCI inputs on biomass production operations (NZ field trials and literature values)

This section describes the process of selecting the most appropriate values for a large number of inputs to the LCI that quantify the operations involved in growing and handling JA biomass. This section will set the stage for the section where the methods for designating (choosing or calculating) LCI values for the impacts on energy use and the environment are provided.

Crop management factors in the spreadsheet were obtained from the BTSL field trial research results on JA. Many input factors related to crop management reflect the experience gained during the field research (see JA Protocol document).

There is little experience on which to base the impacts of producing and handling seed tubers. There is only a single cultivar in NZ for commercial use, named Inulinz. Its flowers do not produce fertile seed under NZ conditions, so propagation is vegetative by tubers. The impacts associated with see are therefore the impacts of growing a JA biomass crop plus tuber harvest, reduced in proportion to the fresh mass of the required seed (3000 kg) compared to the fresh tuber mass at harvest (75,000 kg), or 4%.

LCI-selected tractors and diesel fuel use rates

Tractor fuel use was a major variable contributing to energy use and GWP and, since recording tractor fuel use during field trials was not practicable, it was necessary to rely on research literature. The standard NZ reference on this topic is the Farm Budget Manual published by Lincoln University that includes values on the rate of fuel use in tractors and farm equipment (Faculty of Commerce, 2012). The fuel data source for that manual was the same as used by some of the European studies, the University of Nebraska tractor test lab (web link included in the previous reference). That analysis identified the calculation constant for tractor fuel use to be 0.3L/hr per kW engine size when the engine is working hard, giving fuel consumption as 18 L/hr for a 60 kW tractor or 23 L/hr for a 77 kW tractor. These are the tractor sizes that would be considered for use in NZ during the early years of JA industry development, before very large plantings (that may use larger tractors) are commonplace.

This LCI takes the preferred NZ farming approach for this type of crop, which is to avoid mouldboard ploughing in favour of subsoiling, followed by horizontal rotary cultivation. The NZ manual lists the fuel use for subsoiling as 15 L/ha and for ploughing as 21 L/ha (tractor sizes converge in this calculation, since a larger tractor will cover a hectare more quickly). It seems unlikely that the same tractor using similar diesel fuel would use different amounts of fuel per ha based on geographic differences. However, the reported fuel use values do vary widely, probably due more to soil differences and farming practices. There are several references on fuel use during farming of European biomass species such as giant miscanthus or Mxg (Lewandowski et al, 1995; Bullard & Metcalf, 2001; Teagasc, 2010; Fazio & Monti, 2011) that list tractor fuel use in the range of 20-25 L/ha. The NZ LCA indicated 27 L/ha for Mxg. Average annual fuel use for a perennial JA plantation would probably be similar to Mxg, but this LCA will focus on the year of planting, when fuel use is much higher.

The LCI procedure first chose Calculation Sheet input values of fuel use rates for each farming operation (see Appendix A in the LCA chapter for Mxg). The selected rate for subsoiling, 18 L/ha, is the midpoint of the NZ reference manual values for subsoiling and ploughing, since the subsoiling value seemed too low relative to overseas values. Fuel use for other operations ranged all the way down to 1.0 L/ha, when tractors pull wide implements at higher speed, covering a ha much more quickly. For GWP the emissions from tractor diesel fuel use was calculated for the operation of subsoiling (using 18 L/hr) and this was used as a benchmark for other operation emissions, calculated in proportion to how their listed fuel use compared to that for subsoiling. All calculations of energy inputs were made independently for each operation, since these often were obtained from a range of sources.

The LCI procedure first chose, as spreadsheet input values, the fuel use rate for each farming operation (see Appendix A in the LCA chapter for Mxg). The primary information source was the Nebraska Tractor Test Station measurements of fuel use. Their data were used in the NZ reference (Farm Budget Manual) from Lincoln University, as well some European LCA studies. The selected rate for subsoiling, 18 L/ha, is the midpoint of the values in the manual for subsoiling and ploughing, to avoid under-stating fuel impacts. Fuel use for other operations ranged as low as 1.0 L/ha, when tractors pull wide but light implements at higher speed, covering a ha much more quickly.

LCI-selected fertiliser rate inputs

Fertiliser inputs are important to have right, since research has indicated that N fertiliser is a major contributor to GWP via N_2O emissions (Schmidt et al, 2000) and its production also contributes a large share of the total energy consumed in crop production (Kaltschmitt et al, 1997). The other environmental impact category assessed in this study is eutrophication (EUT). This is primarily impacted by fertiliser use, both P and N. N use has several routes of impact, while fertiliser P has a direct route to waterway eutrophication, but mainly if it is carried to surface waterways with eroded soil.

Nitrogen. The starting point in quantifying N fertiliser inputs is the amount of N removed in the crop. The JA literature indicates up to 0.7% N in harvested dry biomass, which equates with up to 180 kg N/ha removed by a 28 tDM/ha crop.

If soil at the low end of the fertility range supplies 100 kgN/ha then the balance required in fertiliser is 80-100 kgN/ha. This should not be applied until after JA stem emergence. This is to minimise nitrate leaching before the plant root system is well developed to capture nitrate. If JA is managed as a perennial, stem emergence each year can serve as a guide to fertiliser timing.

The LCI procedure used the following N fertiliser rates: 100 kg N/ha following plant establishment. This rate should result in calculated LCA impacts that are as high as likely to be seen among commercial plantings, since the recommended rate for N based on past research ranged from 50 to 100 kgN/ha. The only N response trial in NZ was in 2013, comparing 0 and 120 kgN/ha in plantings of three ages. The only yield increase was in a third-year planting. The trial may not have been definitive, however, since it was a year with low rainfall and yields were only in the 15 to 20 tDM/ha range (compared to 25 to 30 tDM/ha the previous season).

Phosphorus. Crop removal in the harvested crop may be in the 10 to 20 kgP/ha range. Soil should be tested to see if this full rate of replacement is required (it is not if the soil test for P is more than 20 µg/ml). The LCI procedure used as input the rate 23 kg P/ha, which should be incorporated into the soil each year before planting when the soil test for P is low.

Potassium. Crop removal is typically 200 kgK/ha in a biomass harvest, although most NZ soils have large K reserves. The only issue is that mineralised K may not be released quickly enough to supply plants during rapid growth. This is addressed with a typical application of 50 kg K/ha, as used in this LCI.

Lime. Since JA has a wide range of tolerance to soil pH it is not usually necessary to add calcium (lime). None is used in this LCI.

LCI-selected pesticide inputs

JA requires no pesticide inputs for insects or disease. However, weed competition in the first two months is important to avoid. As a low-value arable crop it is not feasible to hand weed, so cultivation or herbicide is needed. The only soil active herbicide labelled for use is pendimethalin (Stomp Xtra) at 1.8 kg (4 litres) per ha, applied soon after planting. Escaped weeds can be hand hoed during the following month, after which the fast growing tall JA plants will out-compete weeds.

Harvest timing inputs

The main determinant of harvest timing is when DM yield peaks, which is in late March or early April. Fortunately, the N content in stems and remaining leaves is quite low, so harvest does not need to wait until after the DM peak, as with giant miscanthus. The other determinant of harvest timing, biomass moisture content, is used for giant miscanthus and triticale in order to time when to bale the biomass. With JA field drying might only be possible after an autumn drought, but the DM yield would be greatly reduced.

The DM yield used in the LCI is therefore based on harvest at the time of peak DM yield, when the biomass is still very high in moisture content. Accordingly, the harvest method is to chop the standing crop with a forage harvester and transport to a drying facility as a pre-step to gasification.

Biomass yield inputs and yield effects on net energy and GWP

The NZ trials with JA provide realistic biomass yield values to assess JA energy yield per ha and the energy balance against inputs. Productivity of JA was quantified in a series of field trials in the Hawke's Bay region of NZ. Under optimal conditions in a site with deep fertile soil the yield can reach 31 tDM/ha in research plots. This should translate into 28 tDM/ha in an optimal commercial planting, but can be 50% lower in a serious drought year. Crops in shallow soils would be affected by drought even more. Another cause of large yield reduction in the first year is planting too late. About 200 days of growth are required prior to plants going into senescence in late March (triggered by shorter days after midsummer). The planting date needs to be in September.

The long-term production trend over the 5–15 years that a perennial JA planting could potentially be sustained is not yet certain, but the expectation is that the running average yield is likely to decline after the first 3 or 4 years. The LCI inputs describe the first year planting; inputs would decrease for subsequent years of a perennial planting, but the largest category (fertiliser) would still be present each year (except in sites with fertile soil). Only after 10 more years of NZ experience with JA shoots as a biomass crop will it be possible to refine the LCA in terms of JA plantation life. The optimal time between replanting could be 5 years like the arable crop lucerne or perhaps 10 (or even 15) years. The growth pattern during the first 3 years is that each year the number of stems per ha increases greatly, but the mass of each stem decreases in proportion.

The LCI input used for dry biomass yield of JA at the farm gate is 95% of 28 t/ha or 26.6 tDM/ha. This yield value is used along with a literature-reported measurement of the Lower

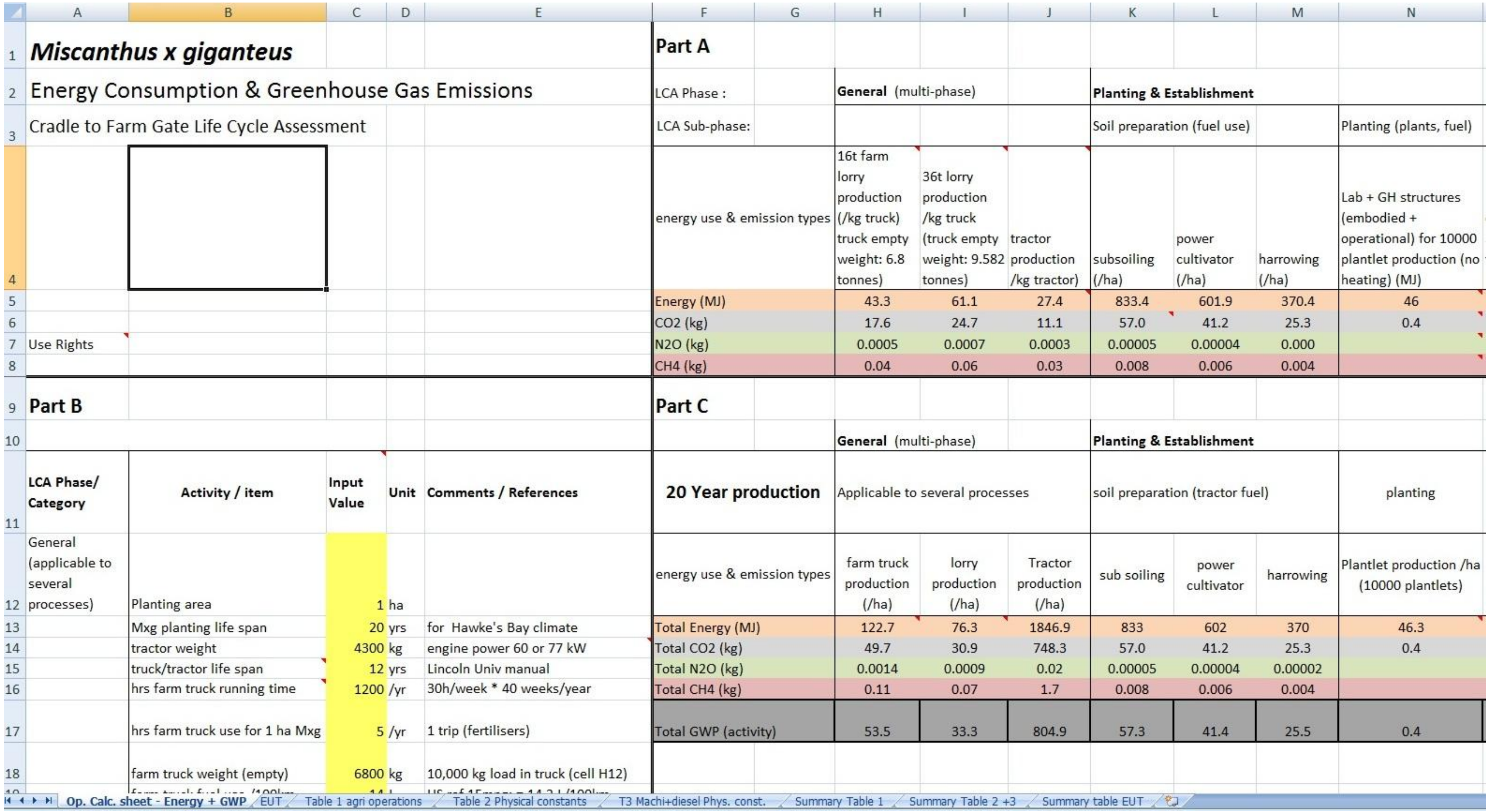
Heating Value (LHV) of JA biomass to calculate the gross and net energy yield (see section on Energy Balance).

Operations Calculation Sheet

Populating the Excel™ calculation spreadsheet with appropriate values constituted the principle task of the LCI process. The three main calculations from the spreadsheet are Energy consumption (GJ/ha) and the two environmental impacts Global Warming Potential (GWP_{100}, as CO_2e/ha) and Eutrophication (EUT100), both on a 100 year basis. Values for these three factors were calculated in a standardised manner, but to one of three different units—either per kg of fertiliser used, per kg of greenhouse gas emissions or per hectare of cropped JA in a single year.

The Operations Calculation Sheet was organised in three parts. See Appendix A, which refers to additional figures and text in Appendix A of the Miscanthus LCA Report. The first two parts are described here and reported in the following subsection of this METHODS section, while the third (spreadsheet results) part is populated with values presented in the RESULTS section.

The JA Operations Calculation Sheet is laid out the same as the one for Mxg (Figure 2), which is an image of the upper left corner of the Sheet. It shows a few columns of Part A in the upper right (with Part C underneath) and a few rows of Part B on the left.



	A	B	C	D	E
1	***Miscanthus x giganteus***				
2	Energy Consumption & Greenhouse Gas Emissions				
3	Cradle to Farm Gate Life Cycle Assessment				
4					
5					
6					
7	Use Rights				
8					
9	**Part B**				
10					
11	**LCA Phase/ Category**	**Activity / item**	**Input Value**	**Unit**	**Comments / References**
12	General (applicable to several processes)	Planting area	1	ha	
13		Mxg planting life span	20	yrs	for Hawke's Bay climate
14		tractor weight	4300	kg	engine power 60 or 77 kW
15		truck/tractor life span	12	yrs	Lincoln Univ manual
16		hrs farm truck running time	1200	/yr	30h/week * 40 weeks/year
17		hrs farm truck use for 1 ha Mxg	5	/yr	1 trip (fertilisers)
18		farm truck weight (empty)	6800	kg	10,000 kg load in truck (cell H12)

	F	H	I	J	K	L	M	N
1	**Part A**							
2	LCA Phase :	**General** (multi-phase)			**Planting & Establishment**			
3	LCA Sub-phase:				Soil preparation (fuel use)			Planting (plants, fuel)
4	energy use & emission types	16t farm lorry production (/kg truck) truck empty weight: 6.8 tonnes)	36t lorry production /kg truck (truck empty weight: 9.582 tonnes)	tractor production /kg tractor)	subsoiling (/ha)	power cultivator (/ha)	harrowing (/ha)	Lab + GH structures (embodied + operational) for 10000 plantlet production (no heating) (MJ)
5	Energy (MJ)	43.3	61.1	27.4	833.4	601.9	370.4	46
6	CO2 (kg)	17.6	24.7	11.1	57.0	41.2	25.3	0.4
7	N2O (kg)	0.0005	0.0007	0.0003	0.00005	0.00004	0.000	
8	CH4 (kg)	0.04	0.06	0.03	0.008	0.006	0.004	
9	**Part C**							
10		**General** (multi-phase)			**Planting & Establishment**			
11	**20 Year production**	Applicable to several processes			soil preparation (tractor fuel)			planting
12	energy use & emission types	farm truck production (/ha)	lorry production (/ha)	Tractor production (/ha)	sub soiling	power cultivator	harrowing	Plantlet production /ha (10000 plantlets)
13	Total Energy (MJ)	122.7	76.3	1846.9	833	602	370	46.3
14	Total CO2 (kg)	49.7	30.9	748.3	57.0	41.2	25.3	0.4
15	Total N2O (kg)	0.0014	0.0009	0.02	0.00005	0.00004	0.00002	
16	Total CH4 (kg)	0.11	0.07	1.7	0.008	0.006	0.004	
17	Total GWP (activity)	53.5	33.3	804.9	57.3	41.4	25.5	0.4

Op. Calc. sheet - Energy + GWP / EUT / Table 1 agri operations / Table 2 Physical constants / T3 Machi+diesel Phys. const. / Summary Table 1 / Summary Table 2 +3 / Summary table EUT

Figure 2. A screen capture from the Operations Calculation Sheet for Giant Miscanthus (as an illustration of a very similar spreadsheet for Jerusalem artichoke). The spreadsheet includes the Life Cycle Inventory for energy consumption and greenhouse gas emissions. Part A columns each characterise a farming operation; Part B contains rows with engineering constants and input variables used to calculate LCI values; and Part C shows the calculated values for the 20-year energy use and emissions in each operations column.

Part A of the JA spreadsheet includes all the operations involved in production of JA biomass, set out across the top of the spreadsheet in 30 columns. The operations are positioned to follow the production sequence, enabling data to be reported clearly in the order of unit processes in the supply chain from cradle to farm gate. These were grouped under two phases: 1) Planting & Crop Growth and 2) Harvest & Handling. There was also a General category for inputs that applied across phases, such as the embodied energy and footprint from manufacturing a tractor. There were 4 rows in Part A, one for energy input (in MJ) and three for the greenhouse gases that contribute most to GWP from use of fuels: carbon dioxide (CO_2), nitrous oxide or dinitrogen oxide (N_2O) and methane (CH_4), all in kg of emissions. Part A shows the rate of energy use or emissions of GHG. Part C looks similar, but shows the total impact for each operation, usually on per ha basis.

Part B of the Operations Calculation Spreadsheet contains a long list of input values that are either engineering constants or selected values of variables assessed in part on how well they fit the observations from the 3-year NZ field trials. Some of these values are illustrated in Tables 1-3. Part B includes the following: (in Table 1) tractor fuel use differences by operation, literature values for rates of fertilisers and herbicides; IPCC values for the relative impact on GWP of the relevant GHGs (not shown here); (in Table 2) the energy content in the triticale biomass produced (to calculate the net energy yield after subtracting energy inputs) and (in Table 3) inputs for embodied energy in farm equipment, i.e. to manufacture, ship to NZ and maintain it.

Table 1: Agricultural inputs for Jerusalem artichoke biomass crop production during the two phases.

LCA Phase	Activity/Product	Unit	Input Values
Planting & Crop Growth	Subsoiling	Runs (/ha)	1
		Fuel use (L/ha)	18
	Cultivating	Runs (/ha)	1
		Fuel use (L/ha)	13
	Harrowing	Runs (/ha)	1
		Fuel use (L/ha)	8
	Planting rate (40k tuber pieces)	kg seed/ha	3000
		Runs (/ha)	1
		Fuel use (L/ha)	6
	Irrigation	(L/ha)	0
	herbicide applications	Fuel use (L/ha)	1
		Runs (/ha)	1
	Fertiliser Applications	Fuel use (L/ha)	3
	N	Runs (/ha)	1
		rate (kg/ha)	100
	P	Runs (/ha)	1
		rate (kg/ha)	60
	K (applied with N)	Runs (/ha)	1
		rate (kg/ha)	60
Harvesting & Handling	Harvest, chopping	Runs (/ha)	1
		Fuel use (L/ha)	6
	Harvest, mowing/tedding	Runs (/ha)	1
		Fuel use (L/ha)	6
	Haul chopped JA to farm gate	Runs (/ha)	1
		Total Fuel use (L/ha)	2
	Total first year fuel use (L diesel/ha, including harvest)		60
	Year 1 fuel use excluding harvest (L/ha-yr)		52

Table 2: Physical constants of the crop (Jerusalem artichoke)

Item	Constant	Unit
Yield (single year, 5 years per site)	26.6	tDM/ha/year
Carbon Content	na	kgC/tDM
Hydrogen Content	na	kgH/tDM
Higher Heating Value (HHV)[2]	18.6	GJ/tDM
Lower Heating Value (LHV)	17.1[1]	GJ/tDM
Crop Gross Energy Yield (LVH x DM)	455	GJ/ha-yr

[1]this value is from triticale; the only JA literature value reported is 18 GJ/tDM

[2]also called GCV and NCV, for gross and net calorific value

Table 3: Diesel and Farm Machinery physical constants (for use with Jerusalem artichoke)

item	constant	unit	source?
Diesel consumer energy (NZ value from MED)	38.4	MJ/L	Energy Data File 2011
Diesel conversion factor from consumer energy to primary energy	1.207		Barber 2011
Diesel primary energy use per litre	46.3	MJ/L	Barber 2011
Diesel GWP (embodied + burning)	3.18	kg CO_2e/L	McDevitt 2011
truck/tractor life span	12	yrs	
tractor weight	4300	kg	
Truck 36t lorry weight	9582	kg	
Farm truck 16t lorry weight	6800	kg	
Tractor standard total use on farm	585	hours/yr	
Tractor use for 1 ha JA operations	6	hours/yr	
Fuel use rate by farm truck	14	L/100km	
Distance (return): fertiliser store to farm	30	km	
Fuel use rate by 36t truck (commercial deliveries)	30	L/100km	
Distance (return): pick up JA seed tubers	200	km	

Part C of the Operations Calculation Sheet is the output or results part, with the cumulative values for inputs for JA production over one year, expressed on per ha basis. The first few columns can be seen in Figure 2. Values are also converted to per ha basis in the case of fertilisers that are on per kg basis in Part A of the sheet. The values derived in Part C of the spreadsheet are reported in the RESULTS section.

LCI-designated impacts of triticale production on energy use and the environment

The following subsections describe the inputs to the Operational Calculation Spreadsheet that quantify energy use and impacts on GWP and EUT of each JA production operation. This procedure generally makes use of LCA software that integrates LCI databases. When software to access such databases is not used (as in this LCA), the required values are compiled or calculated by assessing which values reported from research literature are most appropriate and by using direct knowledge of local (New Zealand) values.

LCI designated inputs on energy use

The calculated rate of energy use for a single operation of each type is shown in Part A of the Operational Calculation Spreadsheet.

<u>Fertiliser impact on energy use.</u> The calculated energy use per kg N in urea is 64.1 MJ/kg, while for calcium ammonium nitrate (CAN) it is 42.5 MJ/kg, both based on values reported in New Zealand studies (Ledgard et al, 2011; Zonderland-Thomassen et al, 2011). The urea value is used here since for arable and biomass crops the more expensive N fertiliser, CAN, is little used. The energy input to make 100 kg N fertiliser (for 1.0 ha of JA) was high, 6407 MJ/ha. Among the other nutrients, phosphorus is the one with the next greatest, but much lower, impact on production energy use (777 MJ/ha) since it is bulky and shipped a long distance (usually from North Africa). The nutrient potassium production energy has the lowest impact at 482 MJ/ha. The energy for tractor fuel to apply fertilisers is 138 MJ/ha. This

is the amount for P fertiliser (applied alone), while N and K are applied together, so each use half that energy.

Diesel tractor fuel impact on energy use. Calculating primary energy input from fuel use was straightforward, since a single NZ –based value was used (46.3 MJ/L of diesel, from Barber 2011a). See Appendix B for an explanation of how this value was chosen, since energy content of fuels does vary with source of petroleum and processing method used. Total primary energy also contains 'fugitive' energy use before the diesel fuel reaches the consumer. In this LCA the value for subsoiling was calculated from fuel use of 18 L/ha and the energy content value of 46.3 MJ/L, or 833 MJ/ha. The other farm operations ranged from 21 MJ/ha for spraying pesticides to 695 MJ/ha for planting tubers.

Pesticide impact on energy use. The LCI procedure for pesticides involved finding input values in MJ/kg active ingredient (ai) in the literature (Bhat 1994; Audsley et al, 2009). The herbicide giving good weed control and that is labelled for use in JA is pendimethalin (Stomp Xtra). It has a fairly large footprint per kg ai (421 MJ) and is applied at a high rate (4L/ha) so the designated input value is 766 MJ/ha.

The herbicide dicamba (Banvel) is used to eradicate JA volunteer shoots after the planting is removed. It is applied during the growth of a cereal grain, which is the best type of crop to follow JA with in a crop rotation. Its energy footprint per kg ai is only 295 and its low use rate gives a modest impact of 41 MJ/ha. Including these two herbicides in the LCI for a single year of JA cropping gives an overestimate of the footprint, since Stomp is only needed in the first year of a perennial planting and Banvel only after the last year.

LCI designated inputs on Global Warming Potential (GWP)

This study has focused on Global Warming Potential (GWP) as the primary environmental impact factor of interest to a project for replacing fossil fuels, which are the main contributors to GWP. The LCI was developed for the calculation of the GWP footprint from the production of JA biomass (as feedstock for biofuel production). While energy use calculations for diesel fuel were able to use a single NZ value for primary energy, the calculation of GWP required formulas using values of emissions for each input product or operation, taken from the literature (e.g., Bullard et al, 2001; Godard et al, 2013; Audsley et al, 2009; Hamelin et al, 2012). The review by Lal (2004) revealed the wide range of GWP values reported for farm operations. When there was not a directly JA-relevant value reported for an operation we opted for the representative value selected in the Lal review.

Fertiliser impact on GWP. This major impact category is often quantified on the basis of carbon dioxide equivalent impacts (CO_2e) per kg of fertiliser product, but it is preferable to do so on the basis of per kg of plant nutrient (elemental N, P or K).

The LCI designated values are:

- For N, the NZ study by Ledgard, et al, (2011) is the source of the GWP values for manufacture of the appropriate fertilisers and shipment to NZ. The calculated GWP for urea is reported as 1.056 kg CO_2e/kg urea (46% N), which converts to 2.296 kg CO_2e/kg N.
- For P, the parallel calculation (in triple superphosphate fertiliser) also used GWP values from Ledgard, et al, (2011). For P on a per kgP basis the reported value 0.596 CO_2e/kg of triple superphosphate (20.5% P) converts to 2.91 kg CO_2e/kg P.

- For K, (in potassium chloride) the GWP per kg KCl (50%K) value is 0.583 (Ledgard, et al, 2011), which converts to 1.17 kg CO_2e/kg K. The P and K elemental analyses used here are from commercial NZ fertiliser (Ravensdown).
- For Lime (calcium carbonate) the GWP value used was 0.396 kg CO_2e/kg lime (Barber, 2011), the IPCC value for loss of CO_2 from soil-applied lime to air.

In the output section of the spreadsheet the above fertiliser impacts on GWP are all converted to per ha basis. By far the largest impact of JA cropping on GWP, as with energy use, was N fertiliser production. Its footprint was 230 kg CO_2e/ha. The P footprint was 67 and K was 58 kg CO_2e/ha. The overall fertiliser summary is shown in the RESULTS section.

A second and larger category of fertiliser impact on GWP is soil emissions of GHGs. These occur in response to application of fertiliser N and lime. The combined (direct and indirect) impact conversion rate for N to N_2O used here is 0.0153. The rate for urea N to CO_2 impact conversion rate is 1.587. The emission impact results for the fertiliser amounts used are presented in the RESULTS section, on per ha basis, since they are calculated in the output section of the spreadsheet (Part C).

Diesel fuel impact on GWP. The LCI designated value was the one published from a NZ LCA study (McDevitt & Sneadon, 2011) since it included the appropriate calculation of impacts from transport to NZ. However, it only presented the collective GWP or kgCO_2e/kg diesel and did not give values for the main individual GHGs, as was the plan in this LCI. Values for N_2O and CH_4 were available from an Ecoinvent report (Nemecek, 2007), so were used instead and subtracted from CO_2e to give values for CO_2.The many other GHGs from diesel combustion (which were excluded here) have even lower emissions than CH_4. Since fuel use is quantified by volume rather than weight, intermediate input values used in the spreadsheet formulas are expressed as kg CO_2e per L before conversion to per ha basis.

The initial calculation of the environmental impact GWP from diesel fuel use was made for the operation of subsoiling, which was used as a benchmark. All other diesel-using operation had their GWP values calculated in proportion to their listed fuel use compared to that for subsoiling.

Pesticide impact on GWP. The LCI procedure designated input values for the two soil active herbicides were not directly available in the literature. The approach used was from an analysis of a very large number of agrichemicals (Audsley et al, 2009) which was able to develop a ‘rule of thumb’ as to how GWP values relate to the production energy values, with a factor of 0.069 times energy use in MJ estimating GWP in kg CO_2e.

The calculated value used in the LCI for pendimethalin is 53 kgCO_2e and for dicamba is 2.8 kg CO_2e. The dicamba GWP footprint is smaller than from burning the one litre of diesel used to apply the herbicide to one ha, but the pendimethalin impact is more significant (although it only occurs in the first year of a perennial JA planting).

Impacts of carbon sequestration below ground. This is an important but still uncertain element in determining the impact of growing a biomass crop on GWP. Quantifying these inputs to soil organic carbon (SOC) is part of calculating the carbon balance from cropping biomass crops. It is calculated as the CO_2 emissions from all processes related to growing the biomass (plus emissions from soil processes) minus the carbon sequestered long-term in the SOC. Several studies have calculated that the best perennial species (that have massive rhizome systems in the soil) will remove more CO_2 than all cropping operations add to the atmosphere as CO_2e (Clifton-Brown et al, 2007; Hansen et al, 2004; Monti & Zatta, 2009) Annual species make little or no such addition to SOC storage and cultivation before planting will reduce SOC through C oxidation. JA grown as a perennial probably has an intermediate benefit to the carbon balance, with a small short-lived rhizome system but a large mass of tubers (15 tDM/ha in year 1). This LCA will not try to estimate the extent of C sequestration and is focused on the impacts of growing JA as an annual crop, which will quantify the worst case scenario for environmental impacts.

Other GWP impact categories. The indirect energy use and embodied GWP were input in the first part of the spreadsheet as values per kg of truck or tractor, etc., so these are only presented in the RESULTS section, after being converted to a per ha basis.

LCI designated inputs on EUT

For the impact category Eutrophication, due to the scarcity of data and budget/time constraints, it was decided to limit the analysis to the emissions from fertilisers use and manufacture and the emissions from the diesel fuel burnt in trucks and tractors during crop production. Fertiliser has been identified as potentially having a large impact on EUT.

EUT was the second environmental impact category chosen. It is defined as the excessive presence of nutrients in water bodies causing uncontrolled growth of vegetation (including algae) that would not have occurred otherwise. The use of crop fertilisers therefore has a high potential to cause eutrophication, due mainly to leaching and soil erosion. The data for calculating EUT are less available than for GWP, but more readily available than data on many of the health and toxicity impact factors. While this focus on fertiliser and fuel use is not comprehensive, it is a reasonable assumption that most emissions affecting eutrophication emanate from these two processes.

EUT is most often expressed in kg PO_4 equivalent, although it is sometimes expressed in kg N equivalent. Emissions of phosphorus and nitrogen and their derivates to the environment constitute the bulk of the EUT sources. In this study, the CML 2001 characterisation factors (updated 04/2013) are used (CML, 2013).

EUT from N emissions

The following CML factors (Table 4) are for the contributing N compounds involved in crop production.

Table 4. Four emission types (forms of N) and the ir sources in the Jerusalem artichoke production system. Many environmental features contribute to the values that have been determined as characterisation factors.

Emission type	Source of emissions	CML Characterisation Factors (1kg = x kg PO_4)
N_2O	Both fuel & fert. use	0.27
NOx	Fuel use	0.13
NH_3 Ammonia	Fertiliser use	0.35
NO_3 Nitrate (surplus)	Fertiliser use	0.1

The step before applying each of these factors is to calculate the emissions of each type from the fertiliser operations used to produce JA biomass. The calculations by several research studies have yielded a range of values. For JA during year 1 the middle of each range was chosen for each factor (Table 5).

Table 5. Referenced emission ratios to quantify N emissions of each type. Values for NOx and NH3 are from Bessou (2012) who cited the Ecoinvent database.

N Emission type/source	Direct ratios	Indirect ratios
N_2O kg/kg diesel	0.000003	Unknown
N_2O as % of N fert.	1.5%	1.5% of N surplus (leached NO_3^-)
NO_x as % of N inputs	0.6%	+1% of volatized NO_x
NH_3 as % of N inputs	2.6%	+1% of volatized NH_3
NO_3^- as % of N surplus	1.0%	Unknown

EUT from P emissions

Erosion and surface runoff are the main sources of phosphorus release into water bodies. However, surface runoff of P can be assumed to be negligible if P fertiliser is incorporated into the soil (unless manure slurry is used). Leaching of P is lower than nutrient N due to its low solubility and strong adherence to soil surfaces.

The following CLM factor is for the contributing form of P fertiliser involved in crop production, expressed as PO_4:

Table 6. The CLM Characterisation Factor applied to surplus P (after plant uptake) from applied fertiliser.

Emission to water	Source of emissions	CML Characterisation Factor (1kg = x kg PO_4)
P (surplus)	Fertiliser	3.06

Soil erosion, however, allows the attached P to be carried to waterways. Erosion rates in the Pacific region of the USA, where the climate is most similar to NZ were about 4 t/ha per yr (all crop/use types). A much lower value was reported from a study of a complete small watershed in Norway (Farkas et al, 2013), where modelled sediment loss in agricultural (arable) soils was only 449 kg/ha with no autumn tillage and 1776 kg/ha with autumn tillage.

For this JA LCA we followed the approach of Hamelin et al (2012) in Denmark. As part of an extensive LCA they summarised several diverse methods recently used to quantify P loss from nutrients applied to the soil and concluded that most results were in line with the simple calculation of losses for annual crop species as 5% of the net surplus of applied P fertiliser (mineral or manure slurry). (If JA EUT were to be calculated for a perennial plantation, P loss would be calculated as 2.5% of the net surplus of P). In the JA EUT calculation sheet we assumed fertiliser P was applied at a rate of 25 kg/ha. Hamelin et al (2012b) presented calculated P losses in a table that assumed 22 kgP/ha was applied to winter wheat, which took up 19 kgP/ha. The cereal crop was followed by a catch crop that took up all of the 3 kgP/ha of net surplus following the grain harvest.

Applying the same approach to a NZ JA crop grown as an annual, fertilised with 23 kgP/ha and with 18 kgP/ha uptake, the net surplus would be 5 kg/ha. P losses would be 5% of that, and that calculated value is used to quantify EUT via the CML Characterisation Factor of 3.06.

Life Cycle Impact Assessment methodology

In addition to the energy balance, the LCIA and chemical flows were developed for two impact categories, both to a 100 year time horizon. These are Global Warming Potential (GWP) and Eutrophication (EUT). For GWP, the characterisation factors used in the LCIA are from the recent AR5 report by the IPCC (IPCC, 2013). The RESULTS section will not specifically do a LCIA, it will be integrated. Background considerations are presented here in METHODS.

Net energy yield (Energy balance)

Determining the net energy balance effects of growing triticale biomass was the key motivation for performing a LCA, since the aim is to use the biomass as feedstock for bioenergy production, mostly as biofuel. The net energy yield at the farm gate is calculated as the gross energy yield (sometimes called the gross energy output) minus energy consumption or usage for the process (Bullard, et al, 2001). Gross energy in the case of JA is energy produced by crop photosynthesis and carried in the crop biomass. Use of the Operations Calculation Sheet will largely be for calculating energy consumption, although it also contains values related to gross energy. The principal analysis will be on the cropping impacts on an area (ha) basis, as used in the first FU. However, for the purpose of the energy yield calculation, these will be converted to per tonne DM basis (as in the second FU), enabling a direct comparison of these inputs costs to the gross energy yield. Net energy yield is then calculated by subtraction of energy consumption from gross energy. It should not be necessary to apportion these measures to individual cropping operations.

Gross energy yield

In addition to the calculation of energy consumption, gross energy yield needs to be calculated using two factors. One is the measured NZ yield of JA dry biomass (converted from trial plot yields to commercial scale yields (31 tDM/ha to 28 tDM/ha) and further reduced by 5% to allow for handling losses in mass during harvest (so 26.6 tDM/ha in a truck passing the farm gate).

The second factor is the energy content of the biomass, expressed as the Lower Heating Value (also called Net Calorific Value). These are expressed on per tonne basis rather than per ha basis. No new measurement of LHV was made with NZ biomass for this study and there is only one published value for JA, 18 GJ/tDM (Rutkaukas et al, 2005). To be conservative, a lower value was used here, 17.1 GJ/tDM. This is the same one used with triticale biomass, which is the LHV for wheat (Fehrenbach 2007).

Energy consumption

The inputs to calculate energy consumption (largely from diesel fuel, fertilisers and pesticides) are all available from literature and were used as inputs in the first part of the Operations Calculation Sheet (Appendix A) for each of the several operations to grow and store triticale biomass. Energy content for diesel fuel and fertilisers imported for use in NZ have been published (see LCI section on page 10). The quantity of diesel fuel used can be calculated with confidence within a reasonable range, as can the required rates of fertilisers, to allow accurate calculation of the impacts. Pesticide requirements for growing JA in NZ are minimal and impacts of the two herbicides can be calculated.

Global warming potential (GWP)

The first of the two environmental impact factors assessed is GWP. It relates to radiative forcing of the gases selected in this LCA to be included in the GWP calculation, expressed as carbon dioxide equivalent (CO_2e). Radiative forcing is “a concept used to make quantitative comparisons of the strength of different human and natural agents in causing climate change. The radiative forcing of a chemical is calculated by quantifying the retained heat due to the presence of a particular gas” (McDevitt, 2011).

GWP, also called the carbon footprint, was chosen as a central environmental impact factor because it is the most reported environmental indicator and there are more readily available data that detail elementary flows for this key impact category. The size of GWP is also of considerable interest to the agricultural export sector as consumers are increasingly ‘environmentally concerned’ and the GWP impact is a widely used environmental indicator reported for food products.

For GWP impacts of crop biomass production for bioenergy, the most relevant greenhouse gases (from use of diesel fuel and fertiliser) are CO_2 (the one used as the standard for comparison), nitrous oxide (N_2O), and methane (CH_4). The appropriate timeframe to assess radiative forcing effects is 100 years (GWP_{100}), rather than 20 or 500 years, as it is the most commonly applied time horizon for GWP in LCA studies. However, the 100 years time horizon assumes that no impacts occur beyond 100 years following a pulse emission, which is not exact but constitutes a standard measure to compare emissions and production systems. Furthermore, GWP_{100} is one of the rare impact categories that does not depend on the site specific conditions of GHG emission, since it is assumed that the gases are “well mixed” in the atmosphere. The 2013 Assessment Report (AR5) (IPCC, 2013) has adjusted the characterisation factors for radiative forcing to 265 for N_2O and 30 for CH_4 to calculate the GWP_{100}. Since new research indicates that CH_4 remains longer in the atmosphere than had been thought, and N_2O alters faster, the new factors represent a decrease for N_2O and an increase for CH_4 compared to the previous IPCC report (IPCC, 2006).

Eutrophication (EUT)

EUT was the second impact category chosen. Eutrophication assesses the excessive presence of nutrients in water bodies causing uncontrolled growth of vegetation (including algae) that would not have occurred otherwise. The use of crop fertilisers therefore has a high potential to cause eutrophication, due mainly to leaching and soil erosion. The data for calculating EUT are less available than for GWP, but more readily available than data on many of the health and toxicity impact factors. For budget/time constraints, it was decided to focus on fuel consumption and fertiliser use as the only sources of eutrophication. While not fully comprehensive, we assumed that most emissions affecting eutrophication emanate from these two processes.

EUT is most often expressed in kg PO_4 equivalent, although it is sometimes expressed in kg N equivalent. Emissions of phosphorus and nitrogen and their derivates to the environment constitute the bulk of the EUT sources.

Cradle to Farm Gate Life Cycle Interpretation (methodology)

The overall LCA interpretation is made in the DISCUSSION section. The focus of this study is on the balance between energy inputs to produce JA biomass for gasification in New Zealand and the energy contained within the biomass feedstock. However, this process of capturing solar energy in plant biomass to replace fossil fuels needs to succeed without creating environmental problems. Therefore, the LCA has also been done in order to quantify two important environmental impacts, GWP and EUT.

RESULTS

This section of the LCA Cradle to Farm Gate report will include the content usually called the Life Cycle Impact Assessment (LCIA). The Life Cycle Interpretation will be included in the DISCUSSION section.

Most results used for the LCIA are generated in Part C of the Operational Calculation Spreadsheet (see Appendix A for details). It has four rows of values that correspond to those in the first part: energy use and rates of emission for three greenhouse gases, as well as a fifth row that calculates the total GWP from the three rows that are for individual GHGs. Figure 3 (in METHODS) includes an example of Part C.

Energy footprint of JA Production

The outputs calculated in the spreadsheet for energy consumption and GWP impacts of JA cropping are summarised in Tables 7 to 9. Table 10 summarises impacts from Table 8 but also expresses impacts on per tonne dry mass basis. The units for energy use are expressed in Gigajoules (1 GJ = 1000 MJ), GWP in kg CO_2 equivalent emissions (kg CO_2e/ha-yr) and EUT emissions to water in phosphate equivalents (kg PO_4e/ha-yr). Each of the table values is the total impact for a key operation or a group of related operations. The tables include all phases of JA cropping.

The overall pattern of energy consumption and GWP is shown in Table 7, presented by production phase and by operation within each phase. Since the table shows the percent of total emissions contributed by each operation, this is called a Contribution Analysis.

Table 7. Contribution analysis of JA farming operations (% of energy consumption and GWP for each operation).

Operations Contribution Analysis Phase	Operation	Energy use (% total Emissions)	GWP_{100} (% total Emissions)
Planting and Crop Growth (P & CG)	Soil preparation	14.0%	9.2%
	Planting + seed inputs	11.8%	9.5%
	Fertiliser (production + transport)	59.8%	26.6%
	Fertiliser (application + field emissions)	1.6%	43.1%
	Agrichemical production + transport	6.3%	4.2%
	Agrichemical application	0.2%	0.2%
	Subtotal P & CG	95.8%	92.9%
Harvest & Handling (H & H)	Mow, tedd & chop	4.3%	2.8%
	Haul to farm gate	0.7%	0.5%
	Subtotal H & H	2.9%	1.9%
Machinery Manufacture	Farm truck (16t) manufacture	0.5%	1.9%
	Tractor manufacture	0.8%	3.3%
		100.0%	99.9%

The main difference between energy consumption and GWP patterns is that Fertiliser production dominates energy use, while the impact of soil emissions of GHGs on GWP was a lot greater than on energy use. The two types of fertiliser impacts make up about 70% of GWP. GWP results are given in more detail on page 30.

Net Energy Yield (Energy Balance) Results

Energy consumption (inputs, GJ/ha)

Values in the third column of Table 8 are the total JA energy use per ha for each of the several operations. The Grand Total of column 3 is the annual energy consumption, 12.9 GJ per ha of JA crop. Note that this excludes the energy required to dry the harvested JA crop down to 18% moisture, to equate with other species stored at that moisture. Fertiliser production, soil preparation and seed production/planting were the largest categories of energy input. The collective impact of diesel fuel use is not apparent in Tables 7 and 8, but is presented later, in Table 9. All other energy inputs were quite minor. Results for the two major inputs are presented in more detail in their own subsections below (fertiliser, diesel fuel). GWP impacts are also detailed in a separate section.

Table 8. Energy consumption, GWP and EUT emissions from Jerusalem artichoke cropping on an area/time basis (/ha-yr). The crop production phases each contain several operations. See Tables 9 and 11 for EUT details.

Impacts: Energy, GWP & EUT **Phase**	**Operation**	**Energy Use** (GJ/ha)	**GWP$_{100}$ (kg** CO2e/ha)	**EUT$_{100}$** (kg PO_4e/ha)
Planting and Crop Growth (P & CG)	Soil preparation	1.81	124	
	Planting + seed inputs	1.52	128	
	Fertiliser (production + transport)	7.70	357	
	Fertiliser (application + field emissions)	0.21	583	
	Agrichemical production + transport	0.81	56	
	Agrichemical application	0.02	3	
	Subtotal P & CG	**12.06**	**1251**	
Harvest & Handling (H & H)	Harvest, Chopping	0.56	38	
	Haul to farm gate	0.09	6	
	Subtotal H & H	**0.65**	**44**	
Machinery Manufacture	Farm truck (16t) manufacture	0.06	26	
	Tractor manufacture	0.10	44	
GRAND TOTAL*	**All phases**	**12.87**	**1366**	**2.74**

***excluding off-farm drying impacts**

The Energy use data in Table 9 are grouped by category, facilitating a comparison between the major contributors, tractor fuel use and fertiliser use, and with minor contributors. In LCA terminology the major contributors are called ‘hotspots.’ Hotspot analysis will be made in the DISCUSSION section.

Table 9. The largest contributors to Energy consumption and GWP emissions, expressed on an area/time basis (/ha-yr).

Impact Contributors **Major categories**	**Energy Use (GJ/ha)**	**GWP_{100} (kg CO2e/ha)**	**EUT_{100} (kg PO_4 eq/ha)**
Diesel fuel used in tractors	3.38	238	
Diesel fuel used in trucks	0.23	20	
Soil preparation	1.81	124	
Seed production	0.62	62	
N Fertiliser production	6.41	230	
P & K Fertiliser production	0.78	67	
N Fertiliser soil emissions	n/a	564	1.97
Pesticide production	0.81	56	
P Fertiliser soil emissions	n/a	n/a	0.77

Fertiliser use

The total energy input for production of N, P and K is 7.7 GJ/ha. Most of this energy (6.4 GJ/ha) is consumed to produce N fertiliser. Details for the other nutrients were presented as part of the LC Inventory description in the Methods section. Compared to the perennial biomass species Mxg (with annualised energy for fertiliser = 1.16 GJ/ha) the fertiliser use and associated energy input for JA is several times higher per ha, due in large part to the higher requirement for N, but also the need for more P and K. JA fertiliser impacts are considerably lower than those of triticale however (11.3 GJ/ha).

Diesel fuel use

Tractor fuel use represents direct energy (primary and 'fugitive') and totalled 3.38 GJ/ha-yr (Table 9). Indirect energy use for manufacture of trucks and farm machinery is much less and is shown in separate rows of Table 8. Compared to annualised fuel use for the perennial biomass species Mxg the fuel use in the first year of a JA planting is more than double due to more farming operations. A perennial planting of JA would have a lower annualised fuel use however, and would use much less fuel than an annual species such as triticale.

Other operations

Compared with fertiliser use and diesel fuel use all other operations in the production of JA biomass have very low energy consumption. While the use of agrichemicals only involves two herbicides, manufacturing one of these (Stomp Xtra) has a high energy cost of 0.77 GJ/ha (but it is only needed in the first year of a perennial JA planting).

JA is propagated vegetatively by tuber pieces, so has the same type of energy costs as producing a biomass crop and in addition the impacts of harvesting, handling and shipping the bulky tubers. Planting the seed tubers is also a slower and more fuel-consuming procedure than planting small seeds such as triticale. However, 3 t/ha of seed is only 4% of a 75 tFM/ha tuber yield and the total energy cost including planting fuel is 0.62 GJ/ha.

With energy consumption of all operations tallied, the next part of an energy balance determination is to calculate gross and net energy yield.

Gross energy output (yield, GJ/ha)

The average biomass yield of a JA crop in this LCA (standing in the field at the time of late summer harvest) is 28 tDM/ha. This is reduced by 5% to calculate the value of the yield loaded at the farm gate (to allow for handling losses), leaving 26.6 tDM/ha per year of available biomass.

Gross energy in the case of crops such as JA is solar energy transformed and stored in the biomass. Gross energy yield is calculated as DM (t/ha) times the energy content. The value used for energy content of 1.0 tDM is the Lower Heating Value (Net Calorific Value). These are expressed on per tonne basis rather than per ha basis. The value used in this LCA is 17.1 GJ/tDM (see Table 2).

JA gross energy yield, therefore = 26.6 tDM/ha multiplied by 17.1 GJ/tDM = 455 GJ/ha.

Net energy yield (to farm gate)

The energy balance at the farm gate is calculated as the gross energy output (or gross energy yield) minus energy input (consumption or usage for the process) (Bullard, et al, 2001).

Net energy yield = gross energy yield (455 GJ/ha) minus energy consumption (12.9 GJ/ha) = 442 GJ/ha-yr.

The energy ratio (at the farm gate) between gross output and gross input was good (455/12.9 = 35). A ratio of 35:1 is considerably higher than the ratio of 22:1 for triticale and sufficiently positive that it may be feasible to produce biofuel from the biomass and still have a sufficiently positive overall energy balance. However, the energy ratio of JA is much lower than that of the perennial species, giant miscanthus (129:1).

Net energy consumption per tonne dry mass

In order for the results of this LCA to be used in the overall Cradle to Grave LCA for biofuel production using biomass from a range of crop species, a second *functional unit* (FU) is required, FU = 1 ton of dry biomass (contained within biomass of specified moisture content, at the farm gate).

For this the net energy yield from the previous section should be expressed on a /tDM basis:

- The energy to produce one tDM of JA equals the energy consumption (12.6 GJ/ha-yr) divided by the DM yield (26.6 tDM/ha-yr), or 0.47 GJ/tDM;
- The gross energy contained in 1.0 tDM of JA equals the gross energy yield (455 GJ/ha-yr) divided by the DM yield (26.6 tDM/ha-yr), or 17.1 GJ/tDM (which is actually the reference value the JA Lower Heating Value used to calculate gross energy yield); and
- The net energy contained in one TDM of JA equals the net energy yield (442 GJ/ha) divided by the DM yield (26.6 tDM/ha-yr), or 16.6 GJ/tDM (also calculated by subtracting energy consumption (0.47 GJ/tDM) from the LHV (17.1 GJ/tDM).

The net energy consumption to grow and harvest Jerusalem artichoke plants containing 1 tDM is shown in Table 10, along with per tonne values for GWP and EUT.

Table 10. JA energy use and GWP per ha or per tonne of dry mass (based on biomass yield of 26.6 tDM/ha).

Energy, GWP_{100} and EUT_{100} emissions basis (and units)	Energy use (GJ)	GWP_{100} (kg CO_2e)	EUT_{100} (kg PO_4e)
Area and time-based emissions (/ha-yr)	12.87	1366	2.74
Emissions per unit dry biomass* (/tDM)	0.48	51.4	0.10

*based on a yield of 26.6 tDM/ha and excluding off-farm drying impacts

Global Warming Potential (GWP) Results

GWP is the principal environmental impact category used in this LCA. Eutrophication results are presented in the next section.

GWP footprint of JA production

The overall GWP of JA production as an annual crop is 1366 kg CO_2e/ha (Table 8, column 4). The calculations for GWP impacts per ha of JA were done in Part C of the Operations Calculation Spreadsheet (Appendix A) for each of the several operations to grow and store JA biomass. Results in the GWP column of Tables 7-10 are from the sum of the emissions from the three GHGs included in this LCA: CO_2, N_2O and CH_4. The totals for each operation are presented in Table 8, column 4.

The contribution analysis (Table 7) reveals that GWP impacts from JA biomass production are similar in one respect to those for energy inputs, in that fertiliser use has the greatest impact. However, the largest impact of fertilisers on GWP was not from their manufacture, but from soil emissions of N_2O and CO_2 from using urea N fertiliser (which makes no impact on energy consumption). Soil emissions caused by N fertiliser (Table 9) has more than double the GWP footprint of either N fertiliser production or diesel fuel, which ranks third.

Fertiliser use

The largest GWP impact (90% greater than from the production of all fertilisers) is from soil emissions of N_2O and CO_2 totalling 564 kg CO_2e/ha (Table 9). This is in reality also an impact of N fertiliser, but an indirect one, involving soil microbes. The small amount of N_2O produced per ha (1.53 kg) has a large impact (405 kg CO_2e/ha) due to its potency as a GHG (265 times that of CO_2). The rest of the field emissions total is from use of a particular form of N fertiliser, urea (adding 159 kg CO_2 per ha) which is included in this LCA since it is the most common N fertiliser form used in arable crops.

The total GWP impact for production of N, P and K is 355 kg CO_2e/ha. Most of this impact is attributable to N fertiliser applied at a rate of 100 kgN/ha (230 kg CO_2e/ha).The P footprint was 67; and the footprint for K was 58 CO_2e/ha.

Diesel fuel use

The GWP emissions related to tractor diesel fuel use totalled 238 kg CO_2e/ha of JA (Table 9). This was the third largest GWP impact, but small compared to the total fertiliser impact.

Other operations

Compared with fertiliser use and diesel fuel use all other operations in the production of JA biomass have very small impacts on GWP. While the use of agrichemicals only involves two herbicides, manufacturing one of these (Stomp Xtra) has a high GWP impact of 52.9 kg CO_2e (but it is only needed in the first year of a planting).

JA planting impacts on GWP, excluding the tractor fuel already included above, are from seed tuber production, which uses 62 kg CO_2e/ha (<5%) of the 1366kg CO_2e/ha total GWP.

SOC Sequestration effect

Note that the above calculated impacts on GWP all exclude any effect on carbon balance of soil organic carbon (SOC) sequestration in the soil around the large structures (tubers and rhizomes) that grow annually in a JA perennial plantation. In the Mxg LCA Report the duration of SOC sequestration was taken to be 7 years out of the 20-year plantation lifespan (before SOC equilibrium is reached). A 7-year long JA plantation could increase the SOC level in the soil during its whole lifespan, since tuber growth already reaches its peak in the first year. This advantage may compensate for the less massive below-ground biomass of JA than Mxg so that the total gain in SOC could be as great as that of the better-studied Mxg crop. As a result it could be postulated that this process in a JA crop could offset a significant part of the GWP. Testing that hypothesis needs to wait on both the uncertainty in the measurement of SOC sequestration in general and research measurements specific to JA.

Eutrophication (EUT) Results

The five sources of EUT from nitrogen compounds (four from N fertiliser and one from diesel emissions) had a total EUT impact of 1.97 kg PO_4e/ha-yr (Table 11). This value includes 1.38 kg PO_4e/ha-yr from the 3.94 kg of ammonia, released from soils after the application of urea fertiliser containing 100 kgN. Ammonia has a CML characterisation factor of 0.35 to convert kg ammonia to kg PO_4e.

Table 11. Eutrophication resulting from JA cropping. The gases emitted following nitrogen fertiliser use are N_2O (which also is emitted from diesel fuel combustion), NOx, NO3 and NH3. Emissions were lower from P than N fertiliser. The Characterisation Factors are from CML (2013), as in Table 4.

Emissions Source	Eutrophication (kg PO_4e/ha-yr)
Diesel fuel use (N_2O)	0.00022
N fertiliser field emissions	1.97
P fertiliser field emissions	0.77
Total kg PO_4e/ha	**2.74**

Phosphorus supply from the regional soils usually requires fertiliser supplementation to replace the P uptake by the crop. Soil testing is used to gauge the application rate needed. This LCI uses a rate of 23 kgP/ha, applied pre-planting. The surplus P after plant uptake is calculated to be 5 kgP/ha; 5% of that or 0.25 kg P/ha is the P loss to waterways estimated by the integrated method of Hamelin et al, (2012). With a CML characterisation factor of 3.06 the EUT impact of P is 0.77 kg PO_4e/ha, considerably less than the contribution from ammonia and N_2O derived from N fertiliser.

The total EUT impact from N and P fertiliser use in JA is 2.74 kg PO_4e/ha-yr. This compares to the EUT footprints for triticale of 3.87 and for giant miscanthus of 0.46 kg PO_4e/ha-yr. If JA were grown as a perennial for several years the annualised value for total EUT would be about midway between that for the N fertiliser emissions alone and the above value, since the P fertiliser impact is only 2.5% of the surplus P in perennial crops rather than 5% as calculated above (Hamelin et al, 2012).

Impacts per tonne DM

The last aspect of the presentation of results is about the choice of units to quantify impacts of JA production. Analyses in the previous sections all quantified energy consumption, GWP and EUT impacts of triticale biomass production on an area basis, which allows comparisons of environmental costs associated with the use of one hectare. Since the amount of biofuel feedstock that can be produced on one ha may differ, another important way to quantify the impacts is per dry tonne of feedstock. That is the measure (shown in Table 10) that can be used directly in an analysis of producing biofuel from biomass. This is one reason a second functional unit was described in this LCA. The second FU is also useful in relation to net energy yield, as illustrated above in the RESULTS subsection Net energy yield.

The JA footprint sizes per tonne dry mass produced are: 0.48 GJ for energy consumption, 51.4 kg CO_2e for GWP and 0.10 kg PO_4e for EUT. Compared to the other two biomass species assessed, these impacts are lower than for triticale and higher than for giant miscanthus. In terms of comparisons within NZ, production of the biomass crop JA has relatively low energy consumption and environmental impacts (GWP and EUT) compared to most current food and feed crops.

DISCUSSION

Life cycle interpretation is a necessary step in an LCA. It involves discussion of the overall dataset and whether the methodologies chosen influenced the LCI results. It also discusses findings in terms of the 'hotspots' for each impact factor studied; in this case the factors are energy consumption, GWP and EUT impacts of the production of JA shoot biomass.

Functional units

The underlying aim in doing Life Cycle Assessment of a product or process is (once the impacts have been examined) to make it feasible to minimise those impacts in the future.

The primary Cradle to Farm Gate functional unit is FU = *cultivation of 1.0 ha of Jerusalem artichoke for shoot biomass during the year of planting.* This definition is necessary since farming inputs are quantified on an area basis, so their energy and environmental impacts need to be quantified this way as well. The impacts on farmland of growing JA biomass and two other New Zealand-grown feedstocks can be compared in terms of the above FU.

A second FU was required in relation to feedstock supply to a gasification plant. In this case FU = *1.0 tonne dry mass of Jerusalem artichoke (contained within biomass of known moisture content, at the farm gate)*. This FU is necessary to consider the impacts per unit of product (in this case per dry tonne of feedstock used for making biofuel).

Another aspect of using this second FU is the need to assess the energy balance in producing JA biomass from Cradle to Farm Gate. A tonne of dry biomass of different species may contain differing amounts of energy (quantified as Lower Heating Value or Net Calorific Value per tonne dry mass). The crop species also have different yields per ha, which means the impacts per tDM will differ since cropping impacts are quantified on per ha basis. These are considered in the Energy Footprint section.

JA longevity as a perennial

The energy and environmental analysis of JA biomass cropping will be more certain once knowledge is advanced on one matter of JA crop biology. Projected yield of JA biomass in a multi-year plantation (up to 10 or 20 years) can only be quantified with any certainty once research has documented shoot DM yields over that long timeframe. Overseas research reports on JA over the past several decades have mostly focused on tuber production and chemistry and do not report shoot DM yield from the same plantation for more than about 3 years (Kays & Nottingham 2008). This was also as long as trial data were collected from the same research plots in this BTSL project in New Zealand. The positive result from those trials was that DM yields in years 2 and 3 did not decline from the very high yield of the first year. That finding lends itself to the conclusion that high biomass yield can be expected for at least four to five years, which is as long as the mainstream crop species lucerne usually yields well. Due to the greater height and better weed competition of JA than lucerne it is likely this result for JA will be sustained for more than five years.

The production of JA biomass in a perennial system has distinct advantages; these include reduced environmental impacts and biomass with smaller stem size for ease of management at harvest. While the detailed assessment in this LCA has focused on new, first-year plantings of JA, it is possible to estimate the impacts of a perennial system by choosing a lifespan to assess and by selecting those operations in the Operation Calculation Sheet that are required in the following years as well. The principal ones are fertiliser use and harvesting. For a 7-year plantation the annualised impacts are the mean of the first-year impacts and six years with the lower impacts in an established JA planting. These latter values for energy consumption and GWP are 8.55 GJ/ha and 985 kg CO_2e/ha. The annualised energy footprint of a 7-year plantation is 9.17 GJ/ha. The annualised GWP is 1039 kg CO_2e/ha.

Some possible issues that could arise in a perennial JA plantation are: appearance of diseases that affect roots; weakening of stems as the population density increases each year when tubers are left in the ground, which could result in difficulty in harvesting and greater risk of lodging (falling over) due to wind; and average tuber size in an older planting becoming too small for effective harvesting. None was a serious issue in the first three years, however.

Energy footprint

The energy footprint is the energy consumption of the operations involved in the production of the crop biomass, including energy used for manufactured inputs to the farm. This is actually only one component of the calculations to compare the direct and indirect energy inputs with the energy output stored in the crop biomass, ready for conversion into biofuel and other energy forms. Net energy yield is the bottom line for one set of calculations, but energy ratio is also a very useful indicator of energy balance in the production system.

For a discussion on the reliability of the energy input values selected for the LCI see the companion LCA chapter on giant miscanthus biomass. To summarise, for those impacts where this LCI uses more conservative values compared to overseas literature (higher energy content of diesel fuel and higher per ha rates of fuel use by tractors) there should be no concern that the LCA results are underestimating the energy footprint of JA biomass cropping in NZ. The studies that do calculate higher energy consumption are usually older and in EU countries, but a comprehensive German manual on farm statistics and procedures (Achilles, 1999) included fuel use and work time per ha and calculated energy values that are consistently lower than used in this LCI for the similar farm procedures.

As detailed in the Energy Balance Results subsection the annual energy consumption to produce JA biomass in NZ is 12.9 GJ per ha of first year JA crop. This equals 0.48 GJ/tDM, which is quite a low value and therefore promising for the use of JA biomass as a feedstock for gasification. A hotspot analysis of JA production is quite simple, as there are two operational categories (Table 9) that constitute 88% of total energy consumption impact.

Diesel fuel impacts on energy consumption

The second greatest energy hotspot is diesel fuel use in tractors. Fuel use, at 3.4 GJ/ha, accounts for 25% of the total energy footprint. Reduction in tractor fuel use can sometimes be realised with improved farming methods. For JA there is also more scope for changing crop management. If a JA planting were to be managed as a perennial plantation for 5 (or up to 20) years, the energy consumption would be lower due to fewer fuel-using operations and seed tuber supply. This would lower the fuel contribution to energy use compared to the number one energy hotspot in this LCA, fertiliser use, particularly N fertiliser use.

While the contribution % of tractor diesel fuel use in JA is a lower share of energy consumption than for giant miscanthus production, the volume of diesel fuel use per ha (and size of fuel energy footprint) for a JA crop is 2.3 times that of the annualised fuel footprint in the perennial species giant miscanthus. This might be reduced by improving JA farming practices as experience is gained, since it is a new commercial species.

Fertiliser impacts on energy consumption

The total fertiliser energy consumption was 7.2 GJ/ha, excluding tractor fuel used for field application. This number one energy hotspot contributes 63% of total energy use during JA cropping. Clearly this is the operation on which to focus efforts for achieving energy footprint reduction. Switching to managing the JA crop as a perennial would not in itself lower the fertiliser use, assuming the soil type required the same rates annually.

However, there is reason to believe it may be possible to lower fertiliser use rates in many soils from the initial recommendations and thereby reduce the energy footprint. This LCA set fertiliser rates at the upper end of the likely range for NZ soils. Overseas JA research reports have usually focused on tuber yield response to N fertiliser and have been quite variable (often showing no increase to even low N rates, such as 50 kgN/ha). Fewer results on shoot DM have been reported, but the one NZ trial on shoot DM response to N fertiliser showed little or no benefit (Renquist, unpublished). Because JA is not yet a widely-grown crop the fertiliser rate recommendations from overseas research trials are likely to be too high (as a precaution) until optimal rates are determined from commercial experience for a range of soils. There is probably scope for lowering fertiliser rates in a JA planting grown either as an annual or as a perennial as much as 50% compared to the values used as inputs in this LCA. In that case, since fertilisers contribute 63% of the energy consumption, the calculated overall energy use would be reduced by 31.5%.

Net energy yield

Net energy yield of JA biomass equals the gross energy yield (455 GJ/ha-yr) minus energy consumption (12.9 GJ/ha-yr) or 442 GJ/ha-yr. The energy ratio between gross yield and consumption is 35 to 1 in the planting year and about 50 to 1 in a perennial planting (assuming biomass yield is sustained). These findings will be used to quantify the full impact of biofuel production from JA in the combined Cradle to Grave LCA in the BTSL project.

Comparison with giant miscanthus and triticale. One result of the net energy comparisons is to illustrate that the energy footprint of each species plays a very minor role in the net energy yields of each crop. The energy content (LHV) used for triticale and JA biomass were the same, so calculated gross energy yield is proportional to DM yield and therefore greater in JA. JA also had a lower energy consumption per ha than triticale, so the net energy yield (gross – consumption) of JA was quite a bit higher than for triticale (442 versus 339 GJ/ha-yr).

A calculation of Mxg gross and net energy yield uses the higher LHV of Mxg, but lower farm gate DM yield, resulting in a net energy yield value of 351 GJ/ha-yr. So JA also has a higher net energy yield value than Mxg. However, the JA value does not take into account the energy required after the farm gate to dry the biomass to the same range of moisture content as would be present in stored Mxg or triticale. A definitive comparison of net energy yield among the three species will require an estimate of the drying energy required to reduce moisture content of JA biomass to 18%, the target level for baling and storing the other two species.

Energy ratio

Perhaps the simplest way to express the energy balance for biomass production is the energy ratio. The ratio for JA (at the farm gate) between gross energy yield and energy consumption was good (442/12.9 = 35:1). Note that this ratio is more sensitive than net energy yield to the size of the energy consumption footprint. This JA ratio is better than that of triticale (22:1), but since the energy footprint of JA is much larger than that of Mxg, the energy ratio of JA is much lower than that of Mxg (129:1). While JA has a greater biomass yield than Mxg (larger numerator), the smaller denominator (energy footprint) in the Mxg energy ratio has the stronger effect. This result (Mxg better than JA) is different than from the net energy yield comparison. Which measure of energy balance to use may depend on what question is being asked.

GWP footprint

GWP is the principal environmental impact category used in this LCA. The overall GWP of JA production as an annual crop is 1366 kg CO_2e/ha, lower than for the annual biomass species quantified in the Triticale LCA chapter which has a GWP of 1905 kgCO_2e/ha. Note that GWPs up to the farm gate for most food and livestock feed crops that Jerusalem artichoke would replace are likely to fall in a range equal or greater than that of triticale, which is relevant to the effect of land use change (LUC).

Diesel fuel impacts on GWP

The second greatest hotspot is diesel fuel use in tractors. Fuel use, at 238 kg CO_2e/ha, accounts for 17% of the total GWP footprint. Reduction in tractor fuel use can sometimes be realised with improved farming methods. If a JA planting were to be managed as a perennial plantation for 7 (or up to 20) years, the diesel fuel component of GWP would be lower due to fewer fuel-using operations. Seed tubers for a new paddock would only need to be sourced after a 7 or 10 year old plantation was removed rather than every year as in this LCA calculation. Seed supply impacts were calculated based growing a JA crop and harvesting all tubers. In practice it would more likely be an internal matter on the farm, using tubers harvested from near the surface when a planting is cultivated with a chisel plow, a recommended procedure for spring weed control in a perennial JA planting. Even these seed tubers would not be needed very often if a JA plantation proves to have a sustained high shoot biomass yield over a full 20 years, equal to the lifespan of Mxg.

Fertiliser impacts on GWP

The most intense hotspot for GWP was fertiliser use in JA cropping, accounting for 63% of the total GWP (70% if fuel for field application is included, as in Table 9). The largest impact of fertilisers on GWP was not from their production, but from soil emissions of N_2O from any type of N fertiliser and from CO_2 soil emissions due to use of a specific N fertiliser, urea, totalling 41% contribution. Either soil emissions or manufacture alone has more than double the GWP footprint of diesel fuel, which ranks third.

<u>Comparison with giant miscanthus</u>. While JA has a lower GWP than most annual crop species, its total GWP in the first year of production is higher than the perennial biomass species, giant miscanthus, which has an overall annualised GWP of only 264 kg CO_2e/ha. The comparison, however, is between an upper estimate of the JA GWP (which assumes that N, P and K fertiliser is used every year at the rates used in its year of planting) and annualised values for Mxg over 20 years (with the assumption that fertilisers are only needed once for P, twice for K and 8 times for N in 20 years). Using lower rates of fertilisers

in Mxg is based on the proven cycling of nutrients to the rhizome system and back into new shoots, while JA nutrient cycling via tubers has not been quantified and is unproven.

Fertiliser use would be little changed in a perennial system if the soil type required the same rates annually. However, as noted in the DISCUSSION sub-section Energy Consumption, the fertiliser rate used in this LCA might reasonably be reduced by half in some soils in either an annual or perennial management system. This would lower the calculated overall GWP by 35%, since fertilisers currently contribute 70% of the GWP.

Other operations

Compared with fertiliser use and diesel fuel use (with a total contribution of 80%) each of the other operations in the production of JA biomass has a very small impact on GWP.

Illustration of the GWP benefit of fossil fuel substitution with JA biofuel

Diesel substitution by biofuel in tractors and other engines has considerable potential to reduce the GWP footprint of NZ agriculture and/or NZ transport. The most direct way to measure the benefits of fossil fuel substitution by biodiesel is to determine the GWP footprint of producing and using the biodiesel and subtract that from the GWP footprint from producing and using the fossil diesel it replaces.

This LCA provides the analysis necessary to quantify this benefit from Cradle to Farm Gate. The findings are quantified per ha, but also per dry tonne of biomass, as needed for any future LCA of the GWP footprint of biodiesel production from the farm gate through to fuel use (Farm Gate to Grave).

While the Farm Gate to Grave LCA has not been done in NZ for JA or the other two biomass species assessed for the BTSL project, an illustration of the overall benefit to GWP footprint was made in the companion report to this one, on Mxg LCA Report. The illustration sourced literature values for biomass to biofuel conversion, using a conservative (high) estimate for GWP of Mxg of about 1 t CO_2e/ha of biomass (19.3 tDM). Since JA crop yield is higher, the estimate for JA processing is 1.38 t CO_2e/ha. Adding the annualised Cradle to Farm Gate GWP of perennial JA (1.1 t CO_2e/ha) gives an overall GWP for JA of 2.48 tCO_2e/ha.

The Mxg LCA Report then equated the fuel yield in the literature, 160 L biodiesel per dry tonne of biomass (Sims et al, 2010), converted to a /ha basis, to the volume of fossil diesel containing the same fuel energy as the biodiesel. For the JA biomass yield of 26.6 tDM/ha the calculated volume of fossil diesel is 3915 L/ha. The GWP footprint just from burning that diesel equals 12.4 t CO_2e/ha. This is 85% of the total fossil diesel footprint (McDevitt & Seadon, 2011). The difference, after subtracting the Mxg JA footprint, is about 10 t CO_2e/ha, which represents the avoided GWP by biofuel end users, per ha of biomass converted to biofuel. This benefit is equivalent to about 4 times the full Cradle to Grave GWP footprint for JA (2.48 t CO_2e/ha). Other literature estimates of Farm Gate to Grave GWP are only 20% of the conservative estimate used here, so the benefit to GWP from substituting diesel with biodiesel could be as great as 20 times the JA Cradle to Grave GWP estimated in this illustration.

The GWP mitigation from fossil diesel substitution with JA biofuel becomes even larger if SOC sequestration in soil around JA tubers is taken into account. If future research confirms this process, the whole Cradle to Farm Gate GWP may be compensated for. Fossil fuel substitution with biodiesel may have an even greater benefit, making it possible to conclude, if confirmed, that producing biodiesel from JA results in net CO_2 removal from the atmosphere.

The Mxg LCA Report also discussed the social and policy dimension of fossil fuel substitution with biofuel. There will be no benefit for climate change if biofuel is used along with all the fossil fuel that would otherwise be used. Policymakers must create disincentives to keep using fossil diesel in order for biofuel use to be truly beneficial. Uncertainty over that occurrence is probably greater than that in these LCA results.

Finally, an important element of the above analysis is the size of the DM yield of the biomass species in question. The biofuel yield and therefore GWP mitigation possible per ha of biomass would have been much lower if the crop yield was only 8-14 tDM/ha, as it is for JA in northern EU countries and for many other crop species even in the most favourable of climates. This suggests there should be a climatic/geographical component factored in when optimising global bioenergy supply. The NZ yield of JA biomass is very high compared to most other parts of the world, reducing per tDM impacts and raising the potential for mitigation of diesel fuel impacts.

EUT footprint

The overall Eutrophication impact of JA production is 2.74 kg PO_4e/ha. This study found that diesel fuel impacts on EUT (through N_2O and NOx emissions) were negligible. The hotspots for EUT are clearly fertiliser N and P use. N fertiliser use has the greater impact and much of it is due to the loss of NH3 to air (with deposition to lakes and oceans). The combined N fertiliser emissions made up about 60% of total impact on EUT, with P fertiliser contributing the other 40% to EUT. The environmental loss of P (quantified as PO_4) from a JA planting following P fertiliser is to waterways. For both hotspot categories the impacts relative to the other two biomass species studied found that emissions from JA are smaller than those for the crop triticale (3.87 kg PO_4e/ha) and much greater than those for giant miscanthus (0.46 kg PO_4e/ha-yr). Note that the N and P fertiliser rates in this JA analysis were set at the upper end of the likely range.

A discussion of the EUT findings in this LCA project in relation to research literature findings was presented in the Mxg and Triticale LCA Reports. Those reports also discussed the potential effect of including EUT impact factors other than fertilisers and diesel fuel in an LCA.

Allocation of JA cropping impacts

If only shoot biomass is utilised, then there is no allocation of environmental impacts required. That is the assumption used in these LCA calculations for first-year JA cropping. However, if JA is grown commercially as an annual it might be grown for tubers as well as shoots. In that case the presented energy consumption and GWP impact of first year cropping will be overstated. JA tubers may have a market as seed for new growers (with an estimated market value of $1050/tFM, equal to seed potatoes; there may also be a market for JA tubers as a gluten-free processed food product). In such case, the allocation of impacts will be up to 50% to the tubers if allocation is mass-based (and >50% if price-based allocation is used). That leaves the shoot biomass with a much reduced footprint compared to what was determined in this LCA.

Comparing the three biomass species

Some aspects of a comparison of energy use, GWP and EUT impacts is discussed in the Triticale LCA Report, but is more developed in a separate chapter of the overall LCA.

Uncertainties in calculated LCA values

Reported LCA studies with field production of biomass (and food) crops reveal a great deal of variability between studies and also uncertainty in the values calculated for impact factors such as GWP and energy consumption. A more detailed discussion on the sources of this variability was presented in the LCA Reports on Mxg and triticale.

It remains for future LCA work in biomass crop production to assess how thoroughly JA production impacts on energy use, GWP and EUT were quantified in this LCA. It may then be able to judge whether adding other aspects have practical significance (i.e. considerable increase the overall footprint of energy use, GWP or EUT) or mainly add completeness by fully conforming to the ILCD methodology guidelines.

In addition to the three impact categories quantified, there are several others that are included in a comprehensive LCA study of a manufactured product but were not included in this study. Energy use, GWP and EUT do not completely represent the impacts of JA production on the environment. Impact factors that are also important to assess systems that use inputs such as fertiliser, agrichemicals and fuels include: Acidification, Depletion of resources, Ecotoxicity and Ecosystem services impacts (Millennium Ecosystem Assessment, 2005). As the LC Inventory databases reach sufficient levels of certainty these impacts should also be assessed. In the meantime, it would be premature to use this LCA as a basis to refer to JA biomass production as definitely environmentally beneficial.

Fewer uncertainties in major impact factors for energy use and GWP

Along with mention of the many uncertainties it is worth pointing out the higher level of confidence in calculations of some major life cycle impacts, in particular, manufacture and use of both diesel fuel and fertilisers (other than field emissions from fertilisers). The details of this were presented earlier in this DISCUSSION section, under subheadings on energy consumption, energy yield and fertiliser impacts on GWP.

Data review

Other than the geographical coverage aspect the data review discussion is the same for JA as for Mxg (see the Miscanthus LCA report).

Data quality in this study is reasonable for meeting the intended practical purpose, to compare three crop species for production of feedstock for a gasification plant in order to produce biofuels. From the viewpoint of LCA process in an ILCD context the data quality should be a concern, however. The farming operations input values were not based on data collected from a large sample of commercial producers of biomass; in fact there are no large-scale growers of JA for biomass in NZ. The closest agricultural industry to a future one for JA biomass is the sector growing lucerne.

The other data quality issue is the use of overseas values for impact factor rates, when the calculations may have elements that are based on local aspects that differ from NZ. For the two inputs that had the largest energy and environmental impact, use of fertiliser and diesel fuel, the factor rates had been determined in NZ and the same rates applied to the three crop species being compared.

All datasets would be more useful for LCA if data quality were better. In NZ LCA data quality suffers because of the relative isolation of the country and the newness of the LCA field compared to several European countries. Furthermore, there is no method to quantify variability and uncertainty in unit process data.

Geographical Coverage

The LCA has a primary regional focus on Hawke's Bay NZ. The climatic norms there includes warmer temperatures than arable crops are exposed to in about two thirds of NZ and drier than average summer weather for the country, including the 'summer dry' type of marginal site that is one major type of site for large-scale biomass production in NZ. JA is more drought-limited than Mxg and cannot be grown through the more rainy winter like autumn-sown triticale.

Other JA trial plantings were grown in the far north and far south of NZ. In Northland the crop grew well as an annual, but tubers did not get enough winter chilling for new shoots to grow the following year. In Southland the JA cultivar Inulinz appeared well adapted.

General Discussion Topics

Interfacing the Cradle to Farm Gate LCA with a future Farm Gate to Fuel LCA

There are a few noteworthy issues relating to the use of JA biomass for gasification after it leaves the farm gate:

- JA biomass will have a distinct disadvantage for gasification compared to triticale or Mxg in that it usually has high moisture content at its optimal harvest time. Unlike Mxg there is no quality or nutrient cycling advantage from leaving the crop in the field past the time of peak DM (which occurs for JA in late March or early April). Mowing whole stems and field drying to the point of safe baling has been mentioned in the JA literature, but Hawke's Bay NZ experience is that the number of dry sunny days required to dry a first-year crop with large stems cannot be relied on to occur during the 4 to 6 week harvesting window. There is a better chance in the later crop years of a perennial planting to dry the smaller stems sufficiently for baling.
- The moisture content of chopped JA at the farm gate must be measured to calculate the DM yield within the biomass and to know the environmental impacts per tDM (the flow to the second FU). It will also reveal the tonnage that needs to be trucked to the gasification plant or drying facility, to calculate the efficiency and to optimise logistics. High fresh tonnage (low %DM) will dictate a lower maximum economic hauling distance.
- A low cost source of heat for drying, such as factory process waste heat or geothermal heat, will probably need to be available in the vicinity of the gasification plant in order to use first-year JA biomass. One possible alternative is the use of small-scale or portable drying facilities to enable farm storage of dried JA. A second option is to develop harvester with partial drying capability that coarsely chops JA stems and forms the biomass into large loose pellets. Such a harvester is under development for use with Mxg stems. The amount of moisture to remove is greater for JA than Mxg stems however.

- The place of first-year planting JA biomass in the synchronised overall annual supply of feedstock to the plant will be less flexible than that of other species. Delivery needs to be concentrated into the field harvest season during March and April. The quantity available in the following 10 months will be based on successful field drying of later perennial JA crops, with biomass stored in bales (probably round bales).

Synchrony of feedstock supply

Annual variability is to be expected in the availability of the biomass supply from each feedstock species. A consistent supply schedule to the gasification facility will require careful and flexible management to synchronise deliveries from multiple crop species and many farms. A medium sized gasification plant will consume the crop from about 1 ha per day.

This topic will be addressed in more detail in a short report that compares synchronisation strategies using the three biomass species together to meet gasification plant feedstock supply.

Use of marginal land

This issue is covered in the Miscanthus LCA Report.

CONCLUSIONS

Jerusalem artichoke dry mass yield in New Zealand is exceptionally high, 28 tDM/ha at the crop's late summer peak DM, or 26.6 tDM/ha at the farm gate. The explanation supported by field research in NZ attributes it to a long temperate frost-free growing season relative to Northern Hemisphere locales where the growth of JA has been researched. The longevity of a JA plantation in the mild NZ climate is also likely to be longer than in climates where JA can have low or high temperature damage.

The major hotspots for energy consumption were N fertiliser manufacture and diesel fuel use in tractors; the main hotspot for GWP was N fertiliser soil emissions, followed by N fertiliser manufacture and diesel fuel use; the hotspot for EUT was N and P fertiliser use.

The higher biomass productivity of JA in NZ than other regions enables greater mitigation of fossil fuel GHG emissions on per ha of crop basis (via fuel substitution). This assumes overseas JA crops have similar levels of environmental impacts from growing the crop.

In terms of comparisons within NZ, production of the biomass crop JA has relatively low energy consumption and environmental impacts (GWP and EUT) compared to most current food and feed crops. The JA footprint sizes per tonne dry mass produced are: 0.48 GJ for energy consumption, 51.4 kg CO_2e for GWP and 0.10 kg PO_4e for EUT. Compared to the other two biomass species assessed, these impacts are lower than for triticale and higher than for giant miscanthus. The JA values exclude the impacts of off-farm drying of the JA biomass to 18% moisture, needed with large stems in a first-year JA crop in order to store JA in bales like the other two species.

The production of JA biomass in a perennial system has distinct advantages; these include reduced environmental impacts and biomass with smaller stem size for ease of management at harvest. The estimated annualised energy footprint of a 7-year plantation is 9.17 GJ/ha. The annualised GWP is 1039 kg CO_2e/ha.

The net energy yield from producing the bioenergy crop JA from the cradle to the farm gate is the highest of the three species assessed (442 GJ/ha-yr), due to the higher DM yield. However, the advantage of JA will be reduced once the energy cost of more extensive biomass drying is determined.

The JA energy ratio between gross yield and energy consumption is 35:1 in the planting year and about 50:1 if JA is grown as a perennial. This is better than the ratio for triticale but much lower than that of the perennial species Mxg (129:1). The very small energy footprint is the basis of the exceptionally high energy ratio for Mxg.

The above conclusions need to be tempered in the context of stringent professional LCA standards. System boundary issues do not appear to be major, but the whole procedure required use of less developed datasets than are available for most manufactured products. In addition, the JA species is not yet in commercial production in NZ. Therefore there are no local real world datasets to collect on farm operations as was done in a NZ LCA on arable crops.

JERUSALEM ARTICHOKE RECOMMENDATIONS

To reduce both GWP and energy impacts of JA production the main focus should be on reducing use of N fertiliser below rates assumed in this LCA. This is likely to be more feasible with JA than well-characterised commercial species such as triticale.

The reduction in the GWP and energy footprints by reducing fuel use with improved management may be possible, but switching from fossil diesel to biodiesel in tractors is the means to a much larger benefit (reduced GWP impact).

Another footprint-reducing effort should be on facilitating on-farm drying of JA biomass to enable storage. A focus on the smaller stems in later years of a perennial planting has better chance of success at field drying for baling biomass than with first-year plantings. Alternatively, a low cost source of heat for drying, such as factory process waste heat or geothermal heat, will need to be available in the vicinity of the gasification plant.

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APPENDICES

Appendix A. Operational Calculation Spreadsheet

Populating the Excel™ calculation spreadsheet with appropriate values constituted the principle task of the LCI process. The three main calculations from the spreadsheet are Energy consumption (GJ/ha) and the two environmental impacts Global Warming Potential (GWP_{100} as CO_2e/ha) and Eutrophication (EUT_{100} as PO_4e/ha), both on a 100 year basis. The values are first calculated on a standardised basis, either per kg of fertiliser used or per hectare of cropped JA in a single year.

The spreadsheet is organised in three sections (see the illustrations and description in Appendix A in the Giant Miscanthus LCA Report).

Input Values for Part A of Operational Calculation Spreadsheet

The description of Part A in the Giant Miscanthus LCA chapter applies as well to the spreadsheet for JA, except that the operations for JA cropping can be described in fewer columns, grouped into only 2 phases: 1) Planting & Crop Growth; and 2) Harvesting & Handling.

Appendix B. Diesel energy value calculation.

Since diesel is derived from petroleum and its energy content varies in different sources of petroleum, as well as due to refining processes, there are many values in use by engineers. In this analysis the value used was based on the International Energy Agency definition of the energy content of 1.0 tonne of oil equivalent (toe) as 10.0 kcal or 41.868 GJ/tonne. This is called the Lower Heating Value (LVH) and is also called the Net Calorific Value. It can be expressed on either a mass basis as above or can be converted to a volume basis using the IEA value for oil density (0.853 kg/L). The volume basis value by the above calculation is 35.67 MJ/L. This value would be an acceptable choice to use as the energy content at the point of consumption anywhere that a locally-developed value is unavailable, but it should be noted that it does not include the 'fugitive' primary energy expended before the diesel fuel reaches the consumer. The value 35.67 is also appropriate to use in the analysis to calculate the energy content of the fossil diesel substituted with biodiesel.

In New Zealand some fuel is refined in the country and some is imported. The Ministry for Economic Development (now MBIE) has calculated the energy content of diesel at the point of consumption as 38.4 MJ/L, on a volume basis as used in most consumer data, such as L/hr or L/ha of diesel fuel use by tractors (MED, 2010). Primary energy use per L of diesel requires adding the additional sources of 'fugitive' energy (diesel, other fossil fuels and electricity) required before the fuel reaches the consumer. Barber (2011) has calculated that these add 0.207 MJ per MJ at the consumer. Using the factor of 1.207, the MED value for consumer energy (38.4 MJ/L) becomes **46.3 MJ/L**.

Diesel References

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