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Biogas Fuel from a Closed-Loop Nitrogen Supply Cropping System

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Final Report

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Executive Summary

This final report covers the "*Novel biomass production for sustainable biofuel using new crop cultivars and legumes in a closed-loop nitrogen supply cropping system for use on marginal land*" (C11X0901) programme. This programme was a three-year programme (June 2009 - July 2012). It was part of the Sustainable Land Management Mitigation & Adaptation to Climate Change 2008/09 (SLMACC-2nd round) investment- scheme of the Ministry of Agriculture and Fisheries (MAF, now MPI), contracted to the New Zealand Institute for Plant & Food Research Limited (PFR).

The programme explored the opportunity to greatly reduce greenhouse gas (GHG) emissions from the use of fossil fuels by farm equipment and rural trucking by substitution with biofuel. Biofuel production on that scale requires purpose-grown energy crops. Our research has designed a novel energy crop production system that also reduces GHG emissions (from the manufacture of N fertiliser) by virtue of its '*closed loop N supply*' feature. The system is for use on marginal land, where these energy crops will not compete with food production.

The research tested the following elements of a closed-loop N supply system: new plant types with high dry mass (DM) yield and high nitrogen (N)-use efficiency, well-adapted new N-fixing legumes, the measurement of the biogas and methane yield per unit of biomass and the use of digestate from a biogas plant compared with fertiliser to grow an energy crop. Once these New Zealand results were obtained we proceeded to do a '*virtual*' analysis as a test of the proposed CLN cropping and biofuel production system.

Following the successful virtual CLN analysis we presented a local scenario for a biogas production plant supplied by crops suited to the Lake Taupo area. The other project aim was to determine the potential scale for use of marginal sites in NZ to provide biofuel to rural areas. Crop models were used to estimate biomass production of the best species in sustainable rotations on marginal lands. This was scaled up by defining and mapping a key category of marginal land (summer water deficit) and calculating the potential biomass yields from using the CLN system on a realistic 5% of such land.

The biofuel component of the CLN system involves conversion of non-woody biomass into biogas using anaerobic digestion (AD), a proven energy technology. Biogas is a biofuel with superior fuel yields per hectare and very positive GHG impact. In addition to fuel substitution, the CLN system with AD replaces some N fertiliser manufacture via return of enough biogas digestate to supply the energy crops. Any system N losses are efficiently compensated by leguminous crops as part of the crop rotation, which could potentially provide an N surplus to food crops from the system.

Jerusalem artichoke (JA) and forage sorghum were identified after screening eight potential biomass crop species/cultivars in year 1 in terms of best dry matter yield and well-adapted to relevant stresses. A year 2 trial at the PFR experimental site at Hastings with the two selected species successfully generated the field data to do a '*virtual*' test analysis of the proposed CLN cropping system during year 3. The year 2 biomass production for sorghum averaged 25 tDM ha^{-1} and for Jerusalem artichoke 16 tDM ha^{-1}. (As a footnote, JA yields >30tDM were achieved in 2012, but the lower 2011 value was used in calculations for this report). During Year 2 we also identified the amount of N required by the energy crops and showed that it did not matter whether the source was synthetic fertiliser or liquid digestate from an anaerobic digestion (AD) biogas plant.

The final component test of the '*virtual*' CLN system was the biogas and methane yield per unit of biomass. We used a laboratory at BOKU, Vienna in late 2011 for *in-vivo* digestion to directly determine the specific methane yield for sorghum and Jerusalem artichoke under NZ conditions. For this we developed a successful system to make silage in vacuum packed bags for safe shipment to Europe and to have the samples be compatible with those in Europe (also ensiled). Lab results showed that the gas yields were at least as high as those estimated by the method used with the tissue samples from the Year 1 screening trials. Specific biogas methane yields were also very much in line with those from biomass crops grown and tested in Europe.

Biogas and methane yield measurement also utilises biomass composition measurements, to relate direct gas yield measurement to the BOKU Methane Energy Value Model. These also enabled us to calculate N balance and system surplus N.

The mapping and area calculation combined with the experimental DM yield data created the basis to estimate the biofuel potential of this novel energy crop production system for NZ marginal lands. The mapping exercise included defining (sub) classes of marginal land and used these as a basis for objective assessment of land use by region. One of these, '*summer dry*' marginal land, was selected to focus on in order to define optimal land use and crop/cultivar combinations. Phenological measurements of sorghum and JA were made in the Year 2 trial for use in the APSIM crop models. The models assessed the most promising combinations of new species and legumes for maximising biomass production (i.e. new sorghum cultivars in combination with lucerne and crimson clover and the perennial Jerusalem artichoke). This predicted biomass yields for the '*summer dry*' marginal land class throughout New Zealand.

Examples of maps were presented to farmers (such as at the Taupo workshop) to show the potential for biofuel crop production in their region. The yields for the southern two-thirds of the country are conservative, based on lucerne DM yield potential rather than those of JA (which in 2012 demonstrated it can even out-yield sorghum if planted in very early spring). The total potential biomass from New Zealand marginal land is over 77M tDM, but our calculation is based on farmers *only* using <u>5%</u> of such sites, yielding about 3.9M tDM.

The biofuel energy production potential was determined by calculating the quantity of biomethane (purified biogas) that could be produced, both from a single biogas plant (the scenario for the Taupo area, discussed below) and for the DM yield from crops on 5% of 'summer dry' marginal land.

Methane yield potential is actually based on the amount of volatile solids (VS) of the biomass, not the total DM. For the crops studied the ash content (non-volatile) was up to 11%, so a conservative DM/VS ratio of 89% was used for our calculations. For the 3.9M tDM from marginal land the yield of VS is 3.5M tVS. Assuming a further 10% loss of biomass in the process of transportation, silage making and loading into the digester this becomes 3.1M tVS. The volume of methane the biomass from this tonnage of VS can produce is therefore 900 million m^3 CH_4 (from only 5% of this class of marginal arable land). Of the calculated total energy contained in the 900M m^3 of methane up to 30% can be used to grow the crop, operate the digester and purify the biogas to fuel grade methane. This leaves a net yield for fuel of 630M m^3. For end users to more easily visualise the yield, this methane equates with 595M litres of diesel. To gauge this yield in terms of total diesel use, it has an energy content of 21.4 PJ, which represents 160 % of the diesel used by the combined Agriculture, Fishing and Forestry Sectors (13.3 PJ in 2010; NZ Energy Data File, 2010).

At the Lake Taupo Workshop (held at 19 June 2012), we presented a local scenario for crops suited to that area. It was based on the operation of a biogas facility owned by fifteen farmers near Vienna (Austria). The scenario made use of an online tool based on a many commercial operations to assess the overall feasibility (KTBL). The Taupo digester would use biomass from 220 ha of land, totalling ~5,100 tVS annually. The annual yield of methane was 1.34M m^3. In energy terms the scenario would yield 45,000 GJ yr^{-1} gaseous fuel, energy equivalent to 1.27M L diesel fuel. A simplified economic analysis provided for the scenario indicated that a CLN biogas system, based on cropping marginal agricultural land can make sense in terms of conventional economics and the given energy costs and technologies available today.

The other key metric is a calculation of how much this change in farming and rural trucking practice would mitigate GHG emissions by the sector. The emissions from 595M litres of diesel (at 73.25 kt PJ^{-1}) are equivalent to 1.57M t CO_2. This conservative figure is only half of the emissions reductions calculated from the Hawke's Bay planting of sorghum. While that is based on higher DM yields than could be attained in many areas of NZ, the benefits could easily be doubled by New Zealand farmers planting a second 5% of their marginal sites to biomass crops for methane fuel.

The aim of this project was to provide a NZ test of the components (individually proven overseas) for the CLN cropping system as a new use for marginal land. This has been achieved. Use of CLN on just 5% of marginal arable land would also make a large contribution to the overall SLMACC objectives by enabling a 1.57M t reduction in GHG emissions form the agricultural sector. Increased security of farm fuel supply and price stability is achieved in the process.

This program has generated a significant interest among various stakeholders (regional groups, councils) and in response several presentations were given generating further interest domestically and overseas. It has produced a series of papers associated to congresses in New Zealand and overseas, and several international journal publications and reviews were published on this and an associated project that shared the field research. Workshops were held during the final phase of the program where the knowledge of the practices and technologies and the closed loop N system potential in marginal land was demonstrated and discussed to industry sector groups, potential regional investors and policymakers.

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1 Introduction

Over the next few decades the New Zealand (NZ) rural sector will be faced with several challenges. The early effects of climate change may demand some land use change. Particularly in areas that suffer from sub-optimal conditions such as summer moisture deficit farmers are eager to explore mitigation options to deal with such problems if they get worse. Land use changes and land use diversification may not only be an appropriate response to challenges posed by climate change, but at the same time may help to address other environmental issues such as erosion, agricultural GHG emissions, agro-chemical use, and nutrient loss (leaching).

Over the same time frame energy provision to the rural sector will become more problematic. The Ministry of Economic Development (MED) New Zealand's Energy Outlook (MED, 2011), considers oil prices to remain elevated at US$ 130/barrel until 2030 in the reference scenario, but also considers that a high oil price scenario could see oil prices gradually rising to reach US$ 170/barrel in 2030, which would equate to a diesel price of NZ$ 2.50/L or NZ$ 70/GJ (in real terms). However, other influential analysts, e.g. IEA chief economist Fatih Birol (Energy Bulletin, 2010), Christophe de Margerie, CEO Total S.A. (Helman, 2011), Kjell Aleklett, President of ASPO International (Aleklett, 2012), consider that due to a stagnating world oil production, political tensions in key producing countries and rapidly rising petroleum demand in Asia, oil prices will not only starkly increase, but that the adequate and timely supply of petroleum products in both developing and OECD countries, will in fact be called into question in the near future.

While being faced with potentially negative consequences from both climate change and increasingly expensive and insecure energy supplies, the rural sector is at the same time focused on minimising business risk and diversifying core primary production away from established markets and products into new areas. This is a declared aim of the farming industry and government policymakers in NZ.

Agricultural greenhouse gases such as CO_2 from burning fossil fuels have better prospects than ruminant methane for reduction in the near term (Murphy *et al.*, 2009; Renquist and Thiele, 2008). Therefore substituting fossil fuels with biofuels is a more feasible step to reduce the agricultural greenhouse gas (GHG) footprint in NZ. Renewed interest in purpose-grown biomass crops stems from this benefit, from the possibility that producing biofuels is a means of land use diversification and no doubt also from concern about the above-mentioned fuel security issues, as noted in a recent strategy document (BANZ, 2011b). Using land that will become increasingly difficult to use for traditional farming for energy production is a sensible approach to address all these challenges and aims at the same time.

Several ways for achieving these outcomes are possible. For example, a Scion Renewable Energy Project investigated in depth (Hall *et al*., 2009a; 2009b) the potential and feasibility for converting marginal agricultural land to energy forestry (or combined traditional, raw material and energy forestry). The projected scenarios showed huge environmental benefit as well as economic indicators that make this approach an interesting option for further consideration. Limitations of this approach are mainly in relation to scale, (outside) capital requirements and a certain lack of compatibility with existing farming operations (either/or crop management as well as import/ export focus rather than self-sufficiency focus).

The '*ideal alternative rural energy solution*' would have to fulfil a large range of, often mutually exclusive, conditions, including production of a high value fuel, that is flexible in its use, produced using crops with very high biofuel yields per hectare on marginal lands, while using minimal inputs, having a low environmental impact and also being as much as possible compatible with existing infrastructure and processes. No energy system can satisfy all of these demands, and the pre-condition of being compatible with existing structures of the rural sector, places additional restriction on technology/system selection, particularly regarding scale. Table 1 gives a non-exhaustive overview regarding the scale fit of various alternative energy systems.

Table 1: The energy requirements of potential rural biofuel developers and the effective scales required for different technologies that convert biomass to biofuel (compared in four annual production levels). The bottom three rows compare the prices of three currently available energy types when produced at the same four scales.

	Annual production level			
	< 1000 GJ y^{-1}	1000 – 100,000 GJ y^{-1}	100,000 – 10,000,000 GJ y^{-1}	>10,000,000 GJ y^{-1}
Energy requirement farmer group / rural community				
Technology scheme available				
Biodiesel scheme				
Grain ethanol scheme				
BTL (biomass to liquid) scheme				
Cellulosic ethanol				
Rural biogas scheme				
Comparison to alternative energy prices				
Natural gas	36$ GJ^{-1} Complete package	20- 12$ GJ^{-1} Plus thousands of dollars y^{-1} for lines and capacity charges	12 – 8$ GJ^{-1} Plus tens of thousands of dollars y^{-1} for lines and capacity charges	~ 8$ GJ^{-1} Plus tens of thousands of dollars y^{-1} for lines and capacity charges
Diesel	42$ GJ^{-1} Complete package	42$ GJ^{-1} Complete package	42$ GJ^{-1} Complete package	42$ GJ^{-1} Complete package
Electricity	70$ GJ^{-1} Complete package	56 – 40$ GJ^{-1} Plus thousands of dollars y^{-1} for lines and capacity charges	40 – 27$ GJ^{-1} Plus tens of thousands of dollars y^{-1} for lines and capacity charges	~ 18$ GJ^{-1} Plus tens of thousands of dollars y^{-1} for lines and capacity charges

This research focuses on a novel cropping system for producing biogas featuring a closed-loop nitrogen (N) recycling system (termed CLN) for use on NZ marginal land. Appendix 1 gives the structure of the research undertaken. The aim of the CLN project was to follow an alternative, but complementary rather than displacing approach – to find an alternative energy source that is land use based. Its aim is to increase energy self-sufficiency amongst the rural sector and hence is aligned with existing production systems and unit scales common in the NZ rural sector, and that can be managed with a high level of sector internal resources.

The second comparison in Table 1 shows the effect of scale on energy prices. Since rurally-produced biogas as fuel would aim to replace diesel over time it is noteworthy that even at the smallest scale diesel is higher priced than natural gas (the fossil version of biomethane). The other comparison that will be relevant when the future cost of biomethane production is studied rigorously (which is *not* the brief of this CLN project) is between biomethane and fossil natural gas (NG). This table shows that the appropriate scale for this comparison is at the 1000 – 100,000 GJ y^{-1} level, which matches the scale of rural AD development. The very low NG prices at much larger scales are accompanied by very high fixed charges and a wholesale price would require a scale of fuel output that would supply 100 to 3,000 heavy vehicles from a single refuelling point.

When comparing conversion technologies used to produce rural farm and transport fuels from biomass the main conclusion from the upper rows of Table 1 is that only biogas production via anaerobic digestion (AD) and the two first generation biofuels, biodiesel from oilseed crops and bioethanol from grain fermentation are a good scale match to the needs of land use-based energy developers. Of these, only biogas used the whole biomass crop and has a high yield of energy per hectare. It has also been evaluated as the most suitable '*rural-scale*' technology (Braun *et al*., 2009), because: 1) it is capable of conserving and recycling the plant nutrients; 2) the technology is very scalable and therefore well-suited for distributed transport fuel production; 3) the AD process converts the biomass from a hectare of land into at least three times more transport kilometres than conversion to biodiesel (see Börjesson *et al*., 2010; BANZ, 2011b) and therefore; 4) replacing fossil fuels with purified biogas to meet farm energy needs and rural transport is a highly effective greenhouse gas (GHG) mitigation strategy for the sector.

A second opportunity to reduce agricultural GHG emissions is by reducing nitrogen (N) fertiliser, produced from fossil gas. World fertiliser production consumes over 1% of the world's energy and produces 1.2% of the world's GHG emissions (Wood and Cowie, 2004). The interest in nutrient recycling as a feature of resilient cropping is what led the CLN research project to choose the biomass conversion technology anaerobic digestion (AD). This energy extraction method does not destroy biomass nutrients, but leaves them in the digestate, which can be moved back to the field to meet crop nutrient requirements in place of synthetic fertilisers (Birkmose, 2007; Mokry *et al*., 2008; Nyord *et al*., 2008; Al Seadi, 2012). One effect of this is to reduce the GHG footprint compared to manure or synthetic N fertiliser (Alburquerque *et al*., 2012; Wulf *et al*., 2006). The proposed system will require a combination of traditional and novel bioenergy crops as feedstock for AD to achieve high and reliable energy yields per hectare under NZ conditions.

This return of N that was removed by the energy crop back to the land in the form of digestate effectively closes the N cycle, which is why we refer to this energy cropping system as a Closed-Loop N system (CLN) (Renquist *et al.,* 2010a; 2010b). Any losses of N during crop growth (e.g. through leaching or atmospheric losses) could be offset by inclusion of annual or perennial legumes, which would be harvested and digested along with the non-legume crops. Thus, if the amount of N fixed by the legume component of an energy cropping system (such as the one we are investigating) outweighs the N losses, a surplus of N in the CLN system would result and this may be used to fertilise land used for food-crop production, further off-setting GHG emissions and reducing the footprint of the food production. Therefore both this effect and fossil fuel substitution for farm and freight vehicles contribute to MAF's Plan of Action.

The biogas yield per ha for energy crops based AD systems is a function of DM yield per hectare (t DM ha^{-1}) and microbial digestibility. A first measure for the digestibility of a feedstock is volatile solids (VS) content (calculated from total solids (DM) minus ash), but the chemical composition of the VS varies strongly between tissues and therefore considerably influences biogas yield. Researchers in Europe have developed and refined a Methane Energy Value model (Amon *et al*., 2007a; BOKU, 2010) for projecting biogas yields from various feed stocks, which is particularly useful when a digester is using a mixture of feedstock species to optimise biogas production.

The ideal purpose-grown crop for AD would be non-woody, highly digestible, have high biomass (and biogas) yield per ha and a small environmental footprint. This is achieved by good nutrient and water use efficiency and reduced agrichemical needs. Perennial crops may have lower energy inputs (and GHG emissions) than annual crops due to reduced tillage and planting requirements. In environments where crop establishment is difficult it may be better to use perennial crops rather than annual crops. Annual crops or dual purpose crops (i.e. suitable for AD feedstock and livestock feed) may give growers more control over seasonal farm operations, and enable them to capitalise on opportunities and/or mitigate risk. Sorghum and maize have received a lot of attention from overseas researchers investigating feed stocks for AD plants (Amon *et al*., 2007a; BOKU, 2010). Sunflower is being investigated for use in areas with shorter growing seasons or greater risk of frost. Jerusalem artichoke is high yielding and has the advantage of being perennial, which removes the costs and risks associated with annual crop establishment. All of these crops have the potential to be dual-purpose.

Product sustainability of agricultural exports is more readily improved in the crop production phase than in later parts of the value chain. The primary sector's dependence on fossil fuels not only lacks economic and environmental resilience but also puts at risk New Zealand's market image overseas. Rural waste streams and purpose-grown crops could be used to meet most primary sector fuel needs by 2040 and (if tree crops are included) could in fact supply a quarter of New Zealand's total energy demand including over half of the transport fuel needs (BANZ, 2011a).

The productive potential of land is limited by both soil and climatic factors, as outlined in the land use classification (LUC) system (Lynn *et al.*, 2009). The LU Classes of particular interest to this CLN study are LUC 3 and 4 (i.e. moderate limitations for arable use), sub-class *s* (soil limitations), with the primary limitation being prone to summer drought. This focus was chosen because there are large tracts of this type of land currently underutilised across much of New Zealand. While land in LUC 3 and 4 can be made highly productive by developing irrigation and using it for dairying, irrigation development may prove to be a less sustainable option. Furthermore, using some of this land for renewable fuel production may become essential for New Zealand's energy security in the future (BANZ, 2011a; BANZ, 2011b).

A key element of the system concept was to test the CLN concept on '*marginal*' agricultural production sites. In Year 1 we assessed marginal land suitable for energy crop production. Criteria were identified and land categorised to guide modelling of biomass productivity across NZ. A literature study identified ten species/cultivars that meet defined criteria as potential energy crops, and four legume crops for high N-fixation ability in relevant marginal conditions. In Year 2 we selected the best two sorghum cultivars and one new species, Jerusalem artichoke, for the main field test to generate the data to construct a '*virtual*' test of the proposed CLN cropping system during the first half of Year 3. The choice of JA was based on preliminary measurements near Christchurch and in Hawke's Bay plus its inclusion in the Kerikeri screening trial (Kerckhoffs *et al.*, 2011).

The Year 2 field trial was designed to generate field measurement data on growth and DM yield of the chosen species, as well as to test the efficacy of fertilising sorghum using the residual liquid digestate from an anaerobic digester once the biogas was produced and collected. Biomass samples from the Year 2 field trial were used to measure biogas and methane production per unit biomass, to combine with biomass yield to quantify methane fuel production on a per hectare basis. The program focussed in its final year (year 3) to construct and assess the '*virtual*' CLN cropping system as a New Zealand test of the CLN components that have each been proven in EU research and practice. The analysis of ensiled samples from the Year 2 trial is to measure methane yield directly in a leading specialised laboratory in Vienna. Combined with the DM yields and tissue composition results the specific methane yield (m^3 kg^{-1} volatile solids) will be used to scale up to yield per hectare (m^3 ha^{-1}). The mapping of marginal land will enable total DM yield of biomass to be calculated, although the total methane yield calculation will be based on the DM yield from only 5% of that marginal land. To portray the biomass conversion technology for end-users and evaluate the economic feasibility a scenario has been developed for use in the Taupo region based on a large biogas plant in Austria cooperatively owned by fifteen farmers (and visited in 2010 by two of the authors, see Appendix 9).

2 Methodology

2.1 DENTIFYING SUITABLE BIOMASS ENERGY CROPS (YEAR 1)

Three sites were chosen to run the trials, Kerikeri (Plant & Food Research experimental station), Hastings (Plant & Food Research experimental station) and Flaxmere (a commercial livestock/cropping farm in the Hastings district). Site and soil characteristics are described in Table 2. Flaxmere and Kerikeri had the two largest trials as these were the two sites that had soils fitting the above (LUC 3/4s; Lynn *et al*., 2009) criteria. The soil limitations at the Flaxmere and Kerikeri sites were a shallow rooting depth and low AWC, making both marginal for arable food crops. However, this limitation was alleviated at Kerikeri by regular irrigation during the very dry 2009-10 season. A smaller field trial was conducted at Hastings to investigate potential yield of Jerusalem artichoke under conditions of moderate soil fertility.

Table 2: Key soil fertility and physical properties for the three trial sites.

Soil physical characteristics adjusted from Soil Bureau (1968), Sutherland *et al*. (1980) and Griffiths (2001).

Site	Flaxmere	Hastings	Kerikeri
Soil name	Pakipaki ash	Mangateretere silty clay loam	Okaihau gravely clay
Rooting depth (mm)	200-300	>600	300-450
AWC (mm)	15-25	100	25-38
Drainage	Poor	Imperfect	Well - moderate
pH	5.6	5.5	6.0
Olsen-P (µg ml^{-1})	52	40	3
CEC (me 100 g^{-1})	13	21	21
Calcium (me 100 g^{-1})	3.5	10.7	9.5
Magnesium (me 100 g^{-1})	0.6	2.4	1.8
Potassium (me 100 g^{-1})	1.1	0.9	0.6
Sodium (me 100 g^{-1})	0.1	0.1	0.3
Anaerobic Min. N (kg ha^{-1})	94	66	165

Eleven crops were trialled at Flaxmere and Kerikeri (Table 3) in a randomised complete block design with three replicates. Plots were 10 m long by 3.75 m wide. Sunflower and forage maize were sown on 4 September 2009 at Kerikeri and 16 November 2009 in Flaxmere; Jerusalem artichoke was sown on 4 September 2009 at Kerikeri and 24 November 2009 in Hastings; Pearl millet and forage sorghum were sown on 5 November 2009 at Kerikeri and 17 November 2009 in Flaxmere. Only one plot of each crop was grown at Hastings, each measuring 15 m long by 5.25 m wide. In all cases maize, Jerusalem artichoke (JA, or topinambur as it is known in Europe) and sunflower were sown by hand in rows 75 cm apart whereas the sorghum and pearl millet were sown using an 8-row seed drill in rows 15 cm apart. JA was also grown at Redcliffs, Christchurch in the South Island. In 2008 JAs were planted in rows 75 cm apart, however in November 2009 new shoots emerged leaving rows on average only 15 cm apart. Four plots that averaged 2.3 m^2 were marked along rows and harvested on 5 May 2010. During winter, dry stems and tubers were harvested to measure total DM. Crops and planting densities are summarised in Table 3.Seedbeds at all sites were prepared using full inversion tillage and power harrowing at Flaxmere and Hastings, and rotary hoeing at Kerikeri. Fertiliser applications at Flaxmere and Kerikeri were prescribed based on the results from fertility analysis (Table 2) with nitrogen supplied at 200 kgN ha^{-1} (urea) at both sites and with 130 kgP ha^{-1} (super-phosphate) applied at Kerikeri only. The Hastings site had no fertiliser applied. At Kerikeri, irrigation (25 mm) was applied weekly from emergence until late February. Irrigation was applied once at Flaxmere (5 January 2010; 25 mm), and none was applied at Hastings.

Table 3: List of crops grown and planting densities in the trials at Flaxmere (Flax), Kerikeri (Keri) and Hastings (Hast).

Species	Common name	Cultivar	Supplier	Comment	Sowing rate (seeds m^{-2})	Sites grown
Helianthus annum	Sunflower	Hysun 38	Pacific seeds	Forage	6.7	Flax, Keri
Helianthus tuberosus	Jerusalem artichoke	Inulinz	Inulinz Ltd	Annual or perennial	3.3	Keri, Hast
Pennisetum glaucum	Pearl millet	Nutrifeed	Pacific Seeds	Late maturing	130	Flax, Keri
Sorghum bicolor	Sorghum	Speedfeed	Pacific Seeds	Early maturing	130	Flax, Keri
Sorghum bicolor	Sorghum	Sugargraze	Pacific Seeds	Sweet, late maturing	130	Flax, Keri
S. bicolor ×S. sudanense	Sorghum	Jumbo	Pacific Seeds	Very late maturing	130	Flax, Keri
S. bicolor ×S. sudanense	Sorghum	Bettagraze	Pioneer	Late maturing	130	Flax, Keri
Zea mays	Maize	38H20	Pioneer	Medium maturity	8.9	Flax, Keri
Zea mays	Maize	33M54	Pioneer	Late maturing	8.9	Flax, Keri, Hast
Trifolium incarnatum	Crimson clover		Kings seeds	Legume	504	Hast
Trifolium repens	White clover			Legume	315	Hast

The aim was for each crop to be harvested at around the ideal time for making silage (i.e. 30 to 38 DM%). However, due to very dry conditions and rapid crop senescence at Flaxmere, sunflower was harvested on 11 March 2010 and all other crops on 19 March 2010. At Kerikeri the crops were still growing so the biomass harvests were staggered as each one reached the target DM% range. At Kerikeri sunflower, maize and JA were harvested on 4 March 2010 and the sorghum and pearl millet crops on 15 May 2010. At Hastings, maize and JA were harvested on 23 March 2010.

At each site maize and sunflower were harvested by collecting 20 plants from the central rows of each plot, JA by collecting 10 plants, and sorghum and pearl millet by collecting a 1 m^2 quadrat within each plot. Samples were weighed, subsampled and oven dried at 70°C until a constant mass was attained. Composition samples from the three replicates at each site were combined to provide one sample for each crop per site for analysis.

A separate trial was established in Hastings to compare the yields of crimson clover with that of white clover as a winter legume. Seed was drilled on 4 May 2010 just below the soil surface (0-1 cm depth), then harrowed and rolled with a Cambridge roller. *Rhizobium spp.* inoculum was used with both legumes. There were four plots of 7 m^2 of each treatment. Plots were harvested on 12 November 2010 and DM yields were measured.

2.2 IDENTIFYING SUITABLE LAND (YEAR 1)

2.2.1 The New Zealand Land Use Capability (LUC) system

Leaving out for now the aspect of government policy in response to global moral issues like biofuel crops versus food crops, the factor that will ultimately determine the final use of New Zealand farm land is the gross margin. If returns from biofuels are greater than the returns the growers are currently receiving from their land then they will consider converting to growing biofuel crops. The highest value land will be that which can grow the highest value food crops, leaving biofuels to be grown on the more marginal lands of their farm. We will first discuss the current NZ definitions then bring in the social components of our view of defining 'marginal land' in the context of biofuel production.

Marginal land for arable production has already been defined under the land use capability (LUC) system (Lynn *et al.*, 2009). Under the LUC system, land that is most suitable for crop production is classified as class 1, land with slight limitations is placed in class 2, land with moderate limitations is in class 3, and land with severe limitations for arable production, but where it is still possible, is classified as class 4 (Lynn *et al.*, 2009). Land that is not suitable for arable production (often because it is too steep) has a classification number of 5 to 8.

2.2.2 Yield limitation category within LUC classes

For the initial phase of this study we have focussed on land within LUC classes 1-4 that is subject to moderate to severe moisture stress (≥50mm water deficit/year) and will focus on crops that will produce higher yields than pasture under dry conditions. Moisture stress was estimated based on the Annual Water Deficit layer of the Land Environments of New Zealand dataset (Leathwick *et al.*, 2003). Areas under moisture stress were defined as those places where the accumulated evaporation exceeds rainfall by more than 50 mm over the course of a year (calculated from monthly data).

2.3 GROWTH OF FORAGE SORGHUM AND JERUSALEM ARTICHOKE (YEAR 2)

Based on the experiments carried out in Year one, we identified two suitable biomass crops for further closed-loop N systems trials, with two rates of N fertiliser. The criteria were very high DM yield (sorghum) and good adaptation to the relevant field stresses (Jerusalem artichoke). (1) Forage sorghum (*Sorghum bicolor*), two cultivars: *Jumbo* (*Sorghum bicolor x Sorghum sudanese*, very late maturing) and *Sugargraze* (sweet *Sorghum bicolor*, late maturing) (2) Jerusalem artichoke (*Helianthus tuberosus*), one cultivar: *Inulinz* was selected. Sorghum was sown on 8 December 2010, at 130 seeds m^{-2} (Pacific Seeds) with an 8-row seed drill in rows 15cm apart; JA was planted by hand on 9 November 2010 at 6.3 seeds m^{-2}, spacing 40cm x 40cm. The seed source was tubers dug from the previous year's experiment.

A two-cut system (two harvests; one harvest mid-season, and one harvest near the end of the growth season) for JA was compared with a single harvest (near the end of the growth season). This was also repeated using plots in their second season (Year 3), with the first harvest much earlier (14 December 2010), stems cut 30 cm above ground and the second harvest (the re-growth) delayed until May. The one-cut plots were harvested on 15 March.

There was also a Year 3 experiment with a new planting of JA at the same trial site, but that compared two planting dates. One was 7 November 2010 (a similar time in mid-spring as the Year 2 '*virtual*' CLN trial), while the other planting date was very early, 9 September 2010. Plots were harvested on three dates, to define that pattern of DM accumulation.

Two rates of nitrogen fertiliser were applied, at 100 and 200 kgN ha^{-1} (as ammonium sulphate). Fertiliser was applied by hand before sowing. Soil test indicated 66 kgN ha^{-1} (anaerobic mineralisable N). The main experiment was a randomised complete block design with four replicates; plot size was 2.4 m x 8 m.

The control of weeds in the JA plots involved a post-planting application of the herbicide *Stomp Xtra* (3 L ha^{-1}). This was done via knapsack sprayer in order to accommodate plot randomisation. Follow-up hand hoeing was done on two occasions during the first 4 weeks of each planting. No further weed control was applied. Weed control in sorghum involved a post-planting application of the herbicide *Alachlor* (4.75 L ha^{-1}) followed with a post-emergence application of *Basagran* (1.75 L ha^{-1}). Irrigation was applied on three occasions (3, 29 November 2010; 2 February 2011; 30 mm each) to maintain optimal plant performance.

The aim was for each crop to be harvested at around the ideal time for making silage (i.e. 30 to 38 DM%). The sorghum harvest procedure was to cut a biomass sample from a length of 1.15 m along 6 rows (0.15 m apart), giving a harvested quadrat area of 1.035 m^2. Stems were counted (which in the cultivar *Jumbo* included several thin tillers) and the plant height (stem length) measured. A DM sub-sample from each quadrat was dried two days at 80°C. The date of main harvest was 19 May 2011, a few weeks after plants had lodged following very strong winds. Two less-lodged plots were left until 30 May before harvesting. Jerusalem artichoke harvest quadrats were 1.6 m x 0.8 m (1.28 m^2) with 8 plants. Plants were cut in the field and measured indoors. Data collected included number of plants (up to 8), number of stems and number of side branches (defined as stems < 18mm diameter). DM was measured as with sorghum. The main date of JA harvest was 11 April 2011. Tubers from harvested plants were dug at final harvest and yield expressed on a per plant basis.

For JA a 2-cut system was trialled (first cut at 22 February 2011; tops were harvested, with 10 cm stalks left). Unfortunately no significant re-growth was observed, so there was no data for the 2-cut system at final harvest.

2.4 DIGESTATE AS N FERTILISER SOURCE FOR SORGHUM (YEAR 2)

This experiment was designed to test the efficacy of biogas digestate as a source of N fertiliser, since the central element of the CLN system is that nutrients from the biomass of one crop will be recycled to the next crop by applying the liquid from the anaerobic digester to the soil prior to making the next planting.

This practice is already widespread in several EU countries and several research papers have examined the underlying science (Albuquerque *et al.*, 2012; Whelan *et al.*, 2009), key aspects of efficacy (Moller and Stinner, 2009; Nyord *et al.*, 2008) and issues such as ammonia volatilisation (Moller and Stinner, 2009; Nyord *et al*., 2008; Wulf *et al.*, 2006).

We assessed the effect of applying digestate by comparison with ammonium sulphate at the same rates of N (100 and 200 kgN ha^{-1}). One sorghum cultivar (*Sugargraze*) was used in this experiment, and sown (13 December 2010) at a similar seeding rate as the main trial. The digestate experiment was a randomised complete block design with four replicates along-side the main trial; plot size was 2.4 x 8 m.

The digestate was sourced from a vegetable processing company (CSI, Hastings). The major biomass input digested by CSI is onion waste, although at the time the digestate was sourced for the CLN field trial there was also a large amount of waste acetic acid being digested. The digestate was therefore more dilute, which resulted in a relatively low concentration of N in the digestate, and required a higher volume of liquid to be applied per unit area of field plot than would usually (and practically) be the case. Digestate was analysed for N and found to contain 660 µgN mL^{-1} (or 0.66 kgN m^{-3}) of N_{total} with 82% of this being present as ammonium, 1% as nitrate, and the remainder as organic N. The total N concentration in digestate from most crop / manure based biogas plants ranges from 3 – 6 kg N/m3 (FNR 2005), however input material N and water content can lead to a relatively wide variation. The digestate was applied to sorghum plots by hand at two rates of N (100 and 200 kg N_{total}). Ammonium sulphate fertiliser was applied to other plots at the same rate. There were four replicate plots per treatment.

Figure 1: The application of the digestate as N fertiliser source in the field trial.

Both field trials were carried out at the Plant & Food Research site at Lawn Road near Havelock North (-39.648°S, 176.841°E decimal degrees). The site has deep, fertile soil with high water-holding capacity, so expected yields were high. This was important because we wished to determine whether digestate could supply N at a rate sufficient to reach high yields.

The harvesting protocol was similar to the previous experiment.

2.5 MEASURING METHANE YIELD (YEAR 1, 2 AND 3)

2.5.1 Mixed laboratory analysis and empirical calculation (Year 1 indirect method)

For the Year 1 laboratory procedure samples were quartered, ground and sieved (1 mm) and analysed for: crude protein, crude fat/lipid, sugars, starch, cellulose, hemicellulose, ash and crude fibre (and components acid detergent fibre, neutral detergent fibre, and lignin) all using standard wet chemistry methodologies at the Nutrition Laboratory (Massey University, Palmerston North).

To use such laboratory analyses of biomass (and especially cost-effective methods such as NIR) in order to calculate the potential and actual methane yield from the biomass requires a multi-year process of calibration. A preliminary alternative use of tissue composition data is to calculate the theoretical maximum amount of methane that could be produced by fully converting biomass to biogas based on the method of Buswell and Müller (1952). This is the approach we took with Year 1 biomass sample composition.

The actual (as opposed to theoretical) yield of methane that these crops would produce if digested was then estimated by comparing our analytical results with those from a large database developed by the EU-AGRO-BIOGAS Forum (BOKU, 2010). This contains hundreds of entries of relevant crop samples that had been both digested to determine actual methane production and analysed to generate associated wet chemistry data used in the Buswell calculation (Buswell and Müller, 1952).

One key term that is reported for each data record in the database is the per cent Convertible Energy (CE%), which is the ratio of the measured amount of methane produced by the crop sample to the Buswell theoretical maximum methane yield (BOKU, 2010). Our determination of the best CE% values to use is detailed in the Results Section 3.6, where the calculations in Table 13 are described.

There were no data available for JA in the EU-AGRO-BIOGAS Forum database (BOKU, 2010) therefore it was not possible to estimate methane production for this crop. This was measured in the BOKU laboratory following the Year 2 experiments designed to test the CLN concept with JA and sorghum.

2.5.2 Ensiling of sorghum and Jerusalem artichoke harvest samples (Year 2)

The optimal range of maturity for ensiling crop biomass is 28-38% DM. Silage sample harvests were made over a range of dates (22 February 2011 to 12 April 2011) to identify best harvest time for DM yield. Therefore, samples were variable in %DM. Samples were chopped to 5 – 15 mm lengths then spread in the sun to dry to an acceptable %DM (≥25%). Samples (750 g) were then inoculated with 2.4 mg of Pioneer 1174 inoculum and vacuum sealed. By the 29th April 2011 the pH had dropped to 4.5 for sorghum and 4.8 for the Jerusalem artichoke samples respectively. Samples were then sent to BOKU for direct measurement of methane production and also analysed at Massey University (Palmerston North) for indirect determination of methane production.

2.5.3 Laboratory methane analysis (Year 2 direct method)

Methane production was measured at the Department of Sustainable Agricultural Engineering, University of Natural Resources and Applied Life Science (BOKU), Vienna. This laboratory has a large number of small-scale anaerobic digesters and a proven protocol (see appendix 2) for measuring biogas and methane yield (see Figure 2).

Figure 2: Prof Thomas Amon in front of the experimental setup, what is measuring the actual production of methane in crops at BOKU (Vienna).

2.6 PHENOLOGY MEASUREMENTS OF SORGHUM AND JERUSALEM ARTICHOKE (YEAR 2)

In order to calibrate the sorghum model in APSIM for cooler New Zealand conditions it was necessary to collect phenology measurements to define plant developmental stages accurately. These measurements included emergence date, leaf emergence rate and flowering date. Leaf numbers were counted at regular intervals during the growing season to get leaf emergence rate. Phenology data were also collected for JA.

2.7 MAPPING '*MARGINAL*' SITES (YEAR 3)

Six maps were created as examples to show the area and location of 'marginal' sites that could be utilised for growing biofuels crops. These were developed by combining a number of map layers to identify the most suitable marginal land for each crop. Initial screening to remove land that is highly productive for food crops (and therefore cannot be classified as '*marginal*' land) was identified using the New Zealand Land Cover Database Version 2 (Thompson *et al.*, 2003; Appendix 3: Table A). This included short rotation cropland, orchards and vineyards. Land that has high value for specific human activities such as cities, parks, was also excluded from the map (Appendix 3: Table A). Anything scored with a 0 is considered not to be marginal land. Vineyards were not considered to be marginal land because of their high value for wine production, although they would be marginal for most other types of food production. It was also not considered socially acceptable to remove indigenous forest to plant crops for biofuels.

The remaining land that is potentially suitable for growing biofuels (depending on profitability) was then mapped according to suitability for growing either sorghum or Jerusalem artichoke. The first stage in producing a map of marginal sites was to estimate the average maximum yields for each area. These were simulated using the computer model APSIM (McCown *et al*., 1996; Keating *et al*., 2003). This potential yield was then modified by a crop suitability coefficient (k), (after Mills *et al*., 2009) and is defined as estimated yield for that (1 ha) area relative to the maximum potential yield for the region, averaged across a number of years (hereafter referred to as the average maximum yield). The crop suitability coefficient (k) accounts for yield reductions due to various soil and climatic limitations in the area. Factors considered in determination of the crop suitability coefficient came from the LRIS database (Newsome *et al*., 2008) and include: growing degree days, soil pH, salinity, stoniness, rocks, drainage, erosion risk, slope and effective water stress (EWS). Tabulated values of the crop suitability coefficient and how it was estimated are given in Appendix 3.

The EWS was calculated as:

EWS = Annual water deficit (mm) – Plant-available water stored in the soil (mm).

The annual water deficit and plant-available water (PAW) data came from the LENZ and FSL layers respectively, of the LRIS database (Newsome *et al*., 2008).

2.8 THE POTENTIAL OF BIOFUEL CROPS TO SUPPLY NZ RURAL FUEL REQUIREMENTS (YEAR 3)

For the purposes of this study arable land that experienced more than 50 mm of water stress per year was defined as marginal land (Renquist *et al.* 2010a). This land can be identified from the Land Environments of New Zealand (LENZ) database (Leathwick *et al.*, 2003), and the climate data and the area of land in each climate zone is given in the discussion.

Weather data was taken from climate stations (NIWA, 2012) in each of these areas, and then biomass production was estimated by the crop growth model APSIM (McCown *et al.*, 1996). Crops were grown for 14 – 31 years depending on the availability of weather data, and yield were averaged across the years. In areas north of Hawke's Bay biomass production was estimated from a summer sorghum – winter wheat rotation. In areas south of Hawke's Bay biomass production was estimated by growing a crop of lucerne. Both sorghum and lucerne are suitable crops for summer dry areas. Parameters used for the APSIM model are given in Appendix 4. Regions with similar temperature and solar radiation profiles but higher water deficits were simulated by growing the crop on a sandy soil that held 73 mm of plant available water, in contrast to the silt loam soil used for most regions, which held 536 mm of plant available water. For environments I3-I6, J2, which had intermediate water holding capacity between environments J1, 3, 4 and B6, B9 but a similar temperate and radiation profile, and sandy loam soil was assumed and an intermediate yield was estimated for this environment.

The potential yields for each region estimated by APSIM were then reduced by 25% to account for factors such as compaction, pests and disease, and other limitations, which cause farmers' yields to be lower than the theoretical potential. This gives the estimated biomass production from each region.

3 Results and Discussion

3.1 IDENTIFYING SUITABLE BIOMASS ENERGY CROPS

3.1.1 Desirable characteristics of a biomass energy crop

There was a wide variety of crops that could be suitable for the CLN system. Desirable characteristics of a biofuel crop identified in the context of this program are:

(1) produces a large amount of biomass with minimal nutrient requirements.
(2) capable of large yield responses to the addition of digestate.
(3) produces a high biogas yield per kg DM.
(4) easy to manage (minimal pest control requirements).
(5) easy to harvest.
(6) can be stored or ensiled.
(7) easy to establish (important on marginal land where crop establishment is much more difficult than on better land. For this reason perennial crops may be preferred to annual crops).
(8) can be established by minimum- or no-tillage techniques, greatly decreasing the loss of soil C and risk of soil loss due to wind and water erosion, which is more of a problem on marginal land.
(9) suited to the particular site limitations (e.g., land prone to moisture stress).

3.1.2 Selection of crops for the initial screening trial

There are a large number of suitable crops that we already have considerable experience in growing in New Zealand, therefore it was considered of little value to include these in the screening trial. These included grasses – perennial and Italian ryegrass (*Lolium perenne* and (*L. multiflorum*), tall fescue (*Festuca arundinacea*), cocksfoot (*Dactylis glomerata*), triticale (*Triticum durum x Secale cereale*); winter leafy brassicas, e.g. canola (*Brassica napus*); bulb crops – turnips (*B. rapa*), swedes (*B. napobrassica*), fodder beets (*Beta vulgaris*); and legumes – tic beans (*Vicia faba*), lucerne (*Medicago sativa*), and red clover (*Trifolium pratense*).

Bulb and root crops can produce a large amount of dry matter (DM), but were generally thought to be less suitable for the CLN system. This is because they cannot be field wilted so have low DM%, reducing transport efficiency and because harvesting the bulbs requires much more energy and greatly increases the loss of soil C, and the risks of soil erosion and nitrate leaching. They are also more difficult to store than crops that can be ensiled, although for the short term (2-4 months) bulbs and roots are easy to store because they can simply be stockpiled beside the digester, provided that the leaves have been removed. If there was a market for the bulbs and roots, such as sugar processing, in New Zealand then use of the tops for biogas would be more feasible.

3.1.3 Selected annual crops

The crops chosen (Table 3) were relatively new crop species/cultivars to New Zealand that were potentially suitable for the CLN system (Renquist and Kerckhoffs, 2012; Kerckhoffs and Renquist, 2012; Appendix 5). Annual summer crops have the advantage of allowing a winter legume to be grown. Two maize hybrids were selected, one long maturing with subtropical parentage and one shorter maturing; both were suggested as successful high biogas yielding cultivars, but by different mechanisms. Maize produces the most biomass of any annual crop. The main need is to make it more N-use efficient. It may be plausible to do this by increasing the planting density of maize to encourage more stem production and less leaf. Increased stem production would lower the N requirements of the crop, making it more favourable for our CLN system. However, increasing the planting density is also likely to increase early water demand of the crop, with negligible increase in final crop yield.

Sorghum and pearl millet produce a large amount of biomass in a short time span. They are also more drought tolerant than maize, making them more suitable for biomass production in many areas of marginal land. Since sorghum and millet are sown late in spring, this also makes them a suitable crop to follow a winter crop, because many winter-sown crops produce the bulk of their biomass in spring. Therefore they appear to be a suitable choice for the closed loop N system. Millet also has lower N requirements than maize. Both are relatively new crops to New Zealand. Recent sorghum trial yields have been poor (Renquist, unpublished; Pioneer Seeds, pers. comm.), however earlier trials gave yields similar to maize in the more northern sites. Therefore, growing sorghum in the screening trial provides the opportunity to study the new subtropical cultivars while clarifying the conditions limiting growth and DM yield in New Zealand.

Forage sunflowers have been included in the screening study because of their low nutrient requirements and suitability to a wide range of environments. It is likely that their biomass yields will be lower than C4 annual grass crops, but there is little data on forage sunflower biomass production in New Zealand. Therefore it was decided to include them in the study.

Hemp has high yield potential under moist conditions, but because of the regulatory issues around commercial growing approved cannabis cultivars, it was decided that this plant was not an option for our trials. Crimson clover is a relatively untested legume in New Zealand, since legumes are predominantly used here for animal feed, and crimson clover is hairy and relatively intolerant of hard grazing. The crop should grow well under New Zealand conditions and produce a large amount of high quality biomass over autumn – spring. Our trials only included spring planted crops, but Crimson clover warrants future testing for use in a CLN system.

Jerusalem artichoke (JA; known as topinambur in Europe) is also a new crop to New Zealand. Being a perennial it has advantages of fewer cultivation requirements, which reduces the risk of soil erosion and nutrient leaching. Since JA aggressively establishes from tubers, this reduces the risk of crop loss at establishment and reduces the need for weed control. However, the tubers may also mean that JA has the potential to become a weed, which is an important fact to consider in this study. Yields of JA stems and leaves (the part used for AD) are lower than many other crops under ideal conditions, but may yield relatively well under marginal conditions due to its low nutrient requirements and energy stored in the tubers. It was decided that the tubers would not be harvested, in order to have results that apply more widely to marginal land that is not suitable for tuber harvest.

Giant miscanthus (the sterile triploid *Miscanthus x giganteus*) appears to be an ideal new biomass crop. It produces a large amount of biomass (5 – 44 tDM ha^{-1}; Saggar *et al.*, 2007), has low nutrient requirements (Christian *et al.*, 2008), and requires only one cut per year. It also has the advantage of being a perennial, which minimises establishment costs and the risk of erosion. However, Miscanthus biomass is too lignified for AD unless it is harvested earlier than for use in combustion (Heaton *et al.*, 2008). Miscanthus is not freely available in New Zealand and so was not included in the screening trial, but there are current biomass trials being conducted in the country. If findings include early harvest tissue quality data they will help decide whether Miscanthus would be suitable for our proposed biogas CLN system.

3.1.4 Dry mass yields

Promising cultivars were trialled at two North Island sites during Year 1 (2009/2010): The following crops were grown: forage sorghum (*Sorghum bicolor*), forage maize (*Zea mays*), pearl millet (*Pennisetum glaucum*), sunflower (*Helianthus annum*) and Jerusalem artichoke (*Helianthus tuberosus*). Total above-ground dry matter (DM) yield was measured when the crops were mature (28 to 38% DM). Very high DM production potential (26 to 34 tDM ha^{-1}) was demonstrated by two maize cultivars, two sorghum cultivars, and one millet cultivar at a well-watered site (Table 4). The early drought impact at the second site in 2009-10 was least pronounced on two forage sorghum cultivars (18 and 21 tDM ha^{-1}), while other crops proved less drought tolerant.

Table 4: Crop yields (t DM ha^{-1}) and dry matter percentages (DM%) for the crops tested at two locations. Flaxmere crops were harvested on 19 March 2010. At Kerikeri, Hysun38 and 38H20 were harvested on 4 March 2010, 33M54 on 8 April 2010 and all other crops on 15 May 2010. Jerusalem artichoke yield is based on shoot DM only (excluding tubers).

		Kerikeri		Flaxmere	
Crop	Cultivar	Yield (t DM ha^{-1})	DM (%)	Yield (t DM ha^{-1})	DM (%)
Maize	*33M54*	33.7	45	13.2	37
Maize	*38H20*	26.0	34	12.0	55
Sorghum	*Bettagraze*	19.5	27	11.0	44
Sunflower	*Hysun 38*	10.4	21	8.1	36
Sorghum	*Jumbo*	30.3	25	20.6	31
Pearl millet	*Nutrifeed*	31.2	29	13.3	29
Sorghum	*Speedfeed*	21.8	26	12.2	38
Sorghum	*Sugargraze*	28.1	24	17.7	27
Jerusalem artichoke	*Inulinz*	15.3[a]	21	15.1[b]	28
LSD		6.1	3	5.3	8.2
F-pr		<0.001	<0.001	0.005	<0.001

[a] Yield at the Redcliffs site was 17.6 t DM ha^{-1}; [b] grown at Hastings site;

Sunflower yielded poorly at both sites (Table 4), either due to drought sensitivity (Flaxmere) or loss of seeds (> 90% loss) to birds (Kerikeri). Use of sunflower as a biogas crop in NZ may only have niche applications, e.g. as a short rotation crop between cereal grain crops in parts of the South Island with adequate summer rainfall.

Maize yields well where there is enough water, but for marginal land with drought issues it is less suitable, as illustrated by the much lower yields at Flaxmere compared to Kerikeri (Table 4). It would be an excellent biomass to biogas crop on better arable sites if there were no issues with food crop competition.

Sorghum (and pearl millet) cultivars had a wide range of DM yields across the two sites, but all late-maturing cultivars grew large amounts of DM under well-irrigated conditions in Kerikeri. In the early summer dry conditions at Flaxmere, however, the sorghum cultivars *Jumbo* and *Sugargraze* produced much higher yields. One issue with sorghum is that it is generally perceived to be a high N-requiring crop. For the high DM yields of the cultivars used, the industry '*rule of thumb*' would be a requirement of 400-500 kgN ha^{-1}. However, the Year 1 Kerikeri sorghum averaged 0.68% N and removed only 204 kgN ha^{-1}. The available soil N from the previous pasture crop was 126 kg available N ha^{-1}. The 200 kgN ha^{-1} in the fertiliser should be theoretically sufficient without soil N depletion. The Year 2 results with sorghum confirmed that the N requirement for biomass (as opposed to seed) production is relatively modest.

Jerusalem artichoke yields (Table 4) were similar in Kerikeri, Hastings and Redcliffs (Christchurch). JA yielded more than sunflower and, although it did not yield as high as sorghum it may be preferable for a purpose-grown AD feedstock because JA is a perennial crop it is likely to have lower energy inputs (e.g. no annual cultivation and planting requirements) and it has fibrous roots, rhizomes and tubers to maintain or increase soil carbon. Another positive feature of JA is its apparently high nutrient (e.g. N) use efficiency (Kays and Nottingham, 2008). Jerusalem artichoke cannot be grown in the warmest parts of NZ except as an annual crop using freshly imported seed tubers from a cooler location. This is because the tuber buds require vernalisation, which proved inadequate at the Kerikeri site as demonstrated by poor emergence of JA in 2010 from tubers remaining in the ground after the trail in the 2009-10 season.

In choosing the best-adapted annual species from among the screening trials to carry forward into the 2010-11 field trial to construct a '*virtual*' test of the proposed CLN cropping system sorghum appeared better than the maize cultivars, despite the higher maize yields in irrigated conditions.

Jerusalem artichoke was selected for the attributes just noted. We later showed that this perennial also has very high DM yield in its first year if planted early (see Section 3.3). The nutrient use efficiency was confirmed in the 2010-11 Year 2 trial which indicated that 100 kgN ha^{-1} is sufficient for vigorous shoot growth and high shoot DM yield (see Section 3.3).

Crimson clover yielded almost twice as much as white clover (Table 4), making it a much better option as a biofuel crop. One possible disadvantage of crimson clover is that it is only a single cut crop; it is not suitable for repeated grazing, unlike white clover. This limits crimson clover as a dual purpose crop for either animal grazing or biofuel.

Table 5: Crop yields (t DM ha^{-1}) and dry matter percentages (DM%) for the two winter legumes grown at Hastings, sown 4 May 2010 and harvested 12 Nov 2010.

	DM%	Yield (tDM ha^{-1})
Crimson clover	24	9.6
White clover	13	5.3
P	0.005	0.018
LSD	4.7	2.9

3.2 IDENTIFYING SUITABLE LAND

3.2.1 Yield limitation category within LUC classes

For the initial phase of this study we have focussed on land within LUC classes 1-4 where crops are susceptible to moisture stress (Figure 3). Our preliminary analysis suggests that the location of annual biomass crops, such as C4 grasses, should be primarily in LUC 3 sites, but that perennial biomass crops may be a good alternative to grazing or hay crops on LUC 4 land, which comprises 10.5% of the land in NZ.

Figure 3: Arable land mapped according to susceptibility to moisture stress. Arable land that experiences moderate to severe stress (≥50mm water deficit/year) is shaded black, arable land that experiences minimal moisture stress is grey.

Potentially arable land that experiences ≥50mm water deficit per year comprises approximately half of all land in LUC classes 1-4 (most of it is in LUC classes 3 and 4). This area includes most of Canterbury, as well as significant parts of Hawke's Bay, Manawatu, The Hauraki Plains and Central Otago. Pockets of land are also found in Northland, Auckland, Gisborne, Southern Coastal Taranaki, Central Wairarapa, Nelson, Marlborough, Otago and Southland.

3.2.2 Niche areas of land for the CLN system

Returns from growing biofuels will be lower than the high value food crops, but there are a number of situations where biofuels may give better returns than crops currently grown on potentially arable land, such as animal feed crops or pasture. These include:

(1) Intangible benefits (community or environmental value). Despite the fact that biofuels may not compete with food crops or animal feeds on a strict $/$ comparison, they may have a high intangible benefit. For example, using tractors powered on biogas may give an organic grower a competitive advantage over one who does not. Biofuels will help a producer become carbon neutral, and a brand that is carbon neutral may be

preferred over similar brands that are not. Biofuels may have additional value in ecotourism industry. Therefore, areas with a high number of ecotourism operators, and growers with a strong eco-friendly branding focus may decide to grow crops for biofuels.

(2) Remote areas. If the distance to market is large, then this decreases profits for growers from food crops and animal feeds. However distance is not a big issue for biogas production, since the digesters can be located near or even on the farm. The '*economy of scale*' issue for biogas production only requires use of biomass from a large farm or several small farms, while liquid fuel production plants need to be '*think big*' in scale. This makes biogas production, unlike liquid fuels, an ideal candidate for providing remote communities and regions with a sustainable local source of fuel. An example of this might be remote areas in the East Cape of New Zealand, where liquid fuel prices are high, and there are few markets for high value crops or animal feed (there are few dairy farms in this area – the main market for animal feed).

(3) Environmentally sensitive areas**.** Regional councils may impose regulations that prevent intensive cropping or dairying in areas where it is desirable to avoid a high N loading, e.g. lakes, rivers or unconfined aquifers. In these situations, a CLN system, which uses plant cultivars that have a deep root system and the capacity to take up a lot of N, may be desirable. Also, the form of N used in the closed loop system is digestate, which is a mixture of immediately available N (ammonium) and slowly available N (organic N) as opposed to most chemical fertilisers, which are all immediately available N. Digestate is also preferable to direct use of green manure or animal manure slurry (Moller and Stinner, 2009). An example of such a situation would be in the Lake Taupo catchment, where Environment Waikato as the local authority is trying to minimize the amount of N getting into the lake ecosystem and therefore dairy farming and the use of N fertiliser is discouraged.

(4) Areas with problem weeds**.** Land may also become marginal if it is infected with weeds that make it unsuitable for animal feed. For example, alligator weed (*Alternanthera philoxeroides*) is a problem weed in Northland (Northland Regional Council, 2009) and is resistant to selective herbicides. It is toxic to stock which means that a contaminated crop or pasture should not be made into silage. However, the presence of alligator weed in a biofuel crop would not cause a problem for biogas production.

(5) Short duration crops. Farmers may well have a few months in between important cash crops which would be suitable for growing a biogas crop. Biogas crops are ideal for such situations because they simply need to produce vegetative tissue, they do not need to produce grain, flowers or fruits like many other crops. Break crops are also suitable for use as animal feeds, but there are situations where the crop may not want to be used for animal feed, e.g. the field may not be fenced for stock, the farmer may not have a water supply for stock, there may not be many grazing animals available in the district.

Most of the decisions involved in the above niche areas are very local (even within a single farm) and are part of the social component to be considered when defining marginal in relation to the benefits of energy cropping.

3.2.3 The social dimension of marginal land

We are also including a social dimension in our definition of marginal land. At the community scale local energy production may be of interest where a community is isolated or focused on organics or eco-tourism. At the farm scale there are also personal preference decisions as to where biofuel crops may fit; for example, paddocks where use of irrigation is too difficult, less profitable or lower priority than use of the water on a higher value crop in another paddock in years when water supply is short.

3.3 GROWTH OF FORAGE SORGHUM AND JERUSALEM ARTICHOKE

Sorghum in the 2011 '*virtual*' CLN experiment produced significantly more above-ground biomass than Jerusalem artichoke (Table 6). This conclusion now appears to be challenged by the results of a Year 3 trial that compared two planting dates on JA DM yield. While results were not able to be used in the CLN analysis and results in this report, they are very relevant to our Conclusions and Recommendations.

The Year 3 DM yield from the early spring planting date was 1.9 times higher than the reported 2011 JA yield. It was also much higher than the yield of the mid-spring planted Year 3 plots (a shoot yield of 31.3 tDM ha^{-1} versus 18.1 tDM ha^{-1}). We would like to repeat the very high yield result prior to science publication. However, this unpublished DM yield is also referred to in Section 3.6 on methane fuel yield.

The mean DM yield of cultivar *Jumbo* was 22% higher that of *Sugargraze*, although this difference was not statistically significant at P=5% when an ANOVA was conducted on just these two treatments. Figures 4a and b are giving an overview of both sorghum and JA at two different dates at the experimental site in Hastings. Shoot N uptake by the three crop species reflected the same pattern as crop yield (Table 6). Total N uptake by JA is not known since the tubers were not analysed for N; because DM yield of shoots plus tubers was similar to that of sorghum, it is likely that total N uptake would be similar. There was some evidence ($P<0.1$) to suggest that crop N content decreased as the amount of biomass produced by the crop increased (Table 6), due to the N being diluted amongst an increasing amount of biomass.

If the biomass in the JA tubers was included then there was no significant difference in yield between sorghum and JA. In practice it is unlikely that the tuber biomass will be harvested due to the increased energy required to harvest them and the large amount of soil disturbance increases the risk of soil erosion on marginal land. There was no increase in DM yield from applying an additional 100 kgN ha^{-1} (Table 8) nor was there any significant plant type by fertiliser rate interaction.

The additional 100 kgN ha^{-1} did increase the N content of the crops and N uptake (Table 7), however increased crop N content is of no value in the CLN system and exposes a larger amount of N to the risk of leaching when the digestate is returned to the same crop area, so additional N supply is not recommended (see also Section 3.4).

Table 6: Crop yields, N content and shoot N uptake for the three crop types grown in the main trial. Means are averaged, as there was no significant interaction for both fertiliser rates.

Cultivar	*Jumbo*	*Sugar-graze*	J. artichoke Shoot	J. artichoke Shoot + tubers	P	LSD (5%)
Yield (tDM ha^{-1})	27.0	22.1	16.3	25.3	<0.001	4.9
N content (%)	0.97	1.11	1.18		0.099	0.20
N uptake (kgN ha^{-1})	251	234	196		0.031	41

Table 7: Crop yields, N content and shoot N uptake for the two N fertiliser treatments in the main trial. Means are averaged, as there was no significant interaction with crop type.

	Fertiliser Rate (kg ha-1)			
	100	200	P	LSD (5%)
Yield (tDM ha^{-1})	22.0	21.6	0.838	4.7
N content (%)	0.96	1.21	0.005	0.16
N uptake (kgN ha^{-1})	205	249	0.013	33

Table 8: Crop yields (tDM ha^{-1}) at two fertiliser rates for each crop type in the main trial.

	Fertiliser Rate (kg ha^{-1})	
	100	200
Jumbo	27.3	26.7
Sugargraze	22.9	21.2
J. artichoke	15.8	16.8

Above-ground biomass of JA increased by 26% between the 22 February and 5 April 2011, when plants were left uncut on the first date (Table 9). The February harvest was part of an experiment to test whether DM yield could be increased by having two harvests (two-cut system). While the general rule is that total biomass is greater if there is no canopy removal during summer, there is research showing that for JA multiple cuts very early in the summer yielded equal or greater total biomass (Rawate and Hill, 1985).

There was no significant re-growth in plots that were harvested on 22 February 2011 (Figure 5). This may have been due to the first harvest date in the two cut system being too late during crop growth or stems being cut too low, leaving insufficient leaf area to enable continued growth. For that reason a second test of the two-cut approach was made during Year 3. This experiment used a second year JA planting with much higher stem population and likely to be more suitable for two harvests. The two-cut plots were cut early (14 December 2010) with stems left 30 cm tall. The crop was left to re-grow until May but the two cuttings each yielded 5.7 tDM ha^{-1}, while the plots with a single cut mid-March 2011 yielded 25.6 tDM ha^{-1} (unpublished). Clearly, cutting a JA crop twice is detrimental to the aim of maximising DM yield. The DM% is also very low in February 2011 (Table 9), let alone December 2010, posing an issue if the biomass is to be ensiled.

Table 9: Effect of harvest date on shoot yield of Jerusalem artichoke. Data are combined across fertiliser treatments because there was no significant effect of applied fertiliser.

Harvest date	Above-ground biomass (tDM ha^{-1})	DM%
22 February 2011	12.9	13.6
5 April 2011	16.3	24.2
P	0.027	<0.001
LSD (5%)	3	1.7

Figure 4a: Overview of the crops grown at the Hastings experimental site (at 5 January 2011). Sorghum (at outsides) was sown 8 December 2010; Jerusalem artichoke was planted 9 November 2010.

Figure 4b: Overview of crops grown at the Hastings experimental site (at 18 February 2011).

Figure 5: Detail of the JA two-cut system (at 15 April 2011). At the forefront are two adjacent JA plots harvested at 22 February for first cut, with no or little re-growth observed.

3.4 CLOSED-LOOP NITROGEN SUPPLY ISSUES

3.4.1 Digestate as N fertiliser source for sorghum

While the use of AD digestate as an alternative fertiliser is not widely practised in NZ the practice is well established and highly valued in northern Europe (Lukehurst, 2009; Al Seadi, 2012). A large incentive for finding alternative N fertiliser sources is the fact that an estimated 1.2% of global total energy consumption is used is for the synthesis of N fertilisers (Wood and Cowie, 2004).

Our experiment on digestate use was primarily to investigate whether it was feasible to supply sufficient N for good crop growth, and determine differences in crop growth due to the different chemical forms of the N supplied. There was no significant effect of fertiliser type or rate on sorghum DM yield (Table 10 and 11). The large yields of biomass with a modest rate of N applied (100 kgN ha^{-1}) as either digestate or ammonium sulphate and a small amount of soil available N (66 kgN ha^{-1} of anaerobically mineralisable N) suggest that sorghum does not require extremely high N fertiliser and is a suitable crop for biomass production in the closed loop N system. This finding was confirmed in the main trial.

Table 10: Sorghum yields and shoot N uptake with two fertiliser types x two rates in the digestate trial.

	Yield (tDM ha^{-1})		N uptake (kgN ha^{-1})	
	Fertiliser Rate (kgN ha^{-1})		Fertiliser Rate (kgN ha^{-1})	
Fertiliser Type	100	200	100	200
Digestate	24.5	25.2	173	217
Ammonium	25.2	24.9	198	276

Table 11: Statistical analysis of sorghum yield and N uptake data for the digestate trial.

Variable	Effect	Digestate	Ammonium sulphate	100	200	Significance (P)	LSD
Yield (tDM ha^{-1})	Fertiliser type	24.8	25.1			0.921	5.4
Yield (tDM ha^{-1})	Fertiliser rate			24.9	25.1	0.931	5.4
N content (%)	Fertiliser type	0.79	0.96			0.048	0.017
N content (%)	Fertiliser rate			0.75	1.00	0.008	0.017
N uptake (kgN ha^{-1})	Fertiliser type	195	237			0.057	44
N uptake (kgN ha^{-1})	Fertiliser rate			185	247	0.012	44

Note there was no significant fertiliser type × fertiliser rate interaction.

Nitrogen uptake in the ammonium fertilised plots was 10 – 32 kg ha^{-1} greater than the sum of what was measured in the soil plus what was added as fertiliser. This may be due to a small amount of N present in the soil below the standard soil sampling depth of 30 cm. It may also be due to the fact that the anaerobically mineralisable N test underestimated the amount of N that would be mineralised during the warm summer conditions (Curtin and McCullum, 2004). A much better measure of N availability in the soil is the plants themselves. Nitrogen uptake in the ammonium fertilised100 kgN ha^{-1} treatment was approximately 200 kgN ha^{-1}, which is very similar to that taken up by crops in the 100 kgN ha^{-1} treatment in the main trial (Table 7). The data suggest that *Sugargraze* grown with 200 kgN ha^{-1}as ammonium sulphate took up 78 kgN ha^{-1} more into the shoots than the 100 kgN ha^{-1} (Table 8). Assuming that approximately 20% of the biomass and N of the sorghum would be in the roots, means the *Sugargraze* probably took up almost all of the extra 100 kg kgN ha^{-1} applied.

Comparing the N uptake of plants grown with ammonium sulphate (which is all water soluble and therefore all immediately available for plant uptake) with that of the digestate (17% of which will be slowly plant available) it is evident that plants supplied with 100 kg N/ha as digestate took up 25 kgN ha^{-1} less than those supplied with ammonium sulphate (Table 10). Sorghum grown with digestate at 200 kg N ha^{-1} took up 59 kgN ha^{-1} less than sorghum grown with ammonium sulphate. Part of these differences can be attributed to the fact that only 83% of the N in the digestate was in the readily available form for the plant.

3.4.2 Application of digestate

The other likely reason for reduced N uptake from the digestate plots is volatilisation of ammonia. A slight ammonia smell was detectable around the test plots for 2 – 3 days after application. The aspect of ammonia volatilisation from alternative fertilisers has been well-studied, as an extension of research on manure management (Van der Meer, 2007). When digestate and undigested manure slurry were applied to the soil surface in a controlled experiment 10% and 9% respectively of the NH_3 was lost in 12 hours, after which time the losses slowed considerably (Moller and Stinner, 2009). The N losses from digestate were slightly higher, presumably since the AD process converts much of the organic N to NH_4-N. The science is now quite mature, including a mass transfer of NH_3 volatilisation from digestate (Whelan *et al.*, 2010) and effects on C and N dynamics in soils (Alburquerque *et al.*, 2012). While it is difficult to keep 100% of the NH_3 within the closed loop system, commercial digestate application technologies have been developed that minimise volatilisation losses. Of the methods researched, soil injection is usually the best (Wulf *et al.*, 2006) and of several injector types the trailing shoe high pressure type was the most effective, reducing NH_3 losses to <3% of total N (Nyord *et al*., 2008). Volatilisation losses of ammonia as part the digestate application of the CLN system cannot entirely be avoided, but appropriate technology selection will help to minimise these losses significantly.

Northern European countries have led the digestate utilisation research over the past decade and it is currently very active in the UK (Anon, 2012). The IEA Task 37 committee is associated with businesses offering commercial technical advice and products that enhance both the AD process and the application of digestate (Al Seadi, 2012; Willems, 2011).

While NH_3 volatilisation is a loss to be managed when applying digestate, it should be kept in mind that the return of digestate to cropland, rather than direct use of crop residues and green manure crops, is a superior approach and a real strength of the CLN cropping system. Möller and Stinner (2009) measured nitrate leaching and nitrous oxide emissions with the use of green manures and crop residues, animal manures, and digestate. It was concluded that "*Biogas digestion of field residues resulted in a win-win situation, with additional energy yields, a lower nitrate leaching risk and lower nitrous oxide emissions*". As a means to achieve the GHG reduction aim of the SLMACC programme, the much lower N_2O production in soil following digestate use rather than residue decomposition is very significant. This is in addition to the primary GHG benefit of displacing fossil fuels with biogas fuels.

3.4.3 Closing the nitrogen loop

The inclusion of a leguminous crop, either as a winter intercrop or perennial legume on a separate plot of land as part of the CLN concept, is a straight forward option for compensating any N losses from the system. A crimson clover crop, sown in early May and harvested mid-November, would easily fit with a sorghum biofuel crop. Crimson clover yielded 9.6 tDM ha^{-1}, which (assuming a shoot N concentration of 2.6%; Evers and Parsons, 2010), would supply 250 kgN ha^{-1}.

In the worst case scenario, the most N that could have been lost by volatilisation in the 100 kgN ha^{-1} treatment is 25 kgN ha^{-1} (the difference in N uptake between the ammonium sulphate and digestate treatment, see Table 10). So the N supplied by a winter crop of crimson clover would supply ten times this amount, thus providing extra N that could be used to fertilise other crops. Plots of tick beans (*Vicia faba*) over winter at the Hastings field site (unpublished) have yielded >18 tDM ha^{-1}, which would supply an even greater amount of N.

To conclude, the issue of NH_3 volatilisation (and other losses in the cycle from fertiliser application to plant uptake to AD fermentation to reuse of digestate) the obvious measure available to offset N losses within the CLN system is to replace some N with N fixed by legumes.

3.5 CALCULATION OF METHANE YIELD PER HECTARE

The methane produced from biomass is often called bio-methane to distinguish it from natural gas (also methane). We are using the term methane for both in this discussion. The best long term means of calculating how much methane can be produced by various biomass sources is to develop a database of both tissue composition (including factors that are not central to animal nutrition) and to make direct methane measurement during anaerobic digestion of samples in a specialised laboratory. Since neither of these were present in New Zealand the Year 1 approach was to start with composition analysis, as a first step towards a database to support use of an existing model of methane yield (Amon *et al.*, 2007a).

Wet chemistry analysis for crude protein, crude lipids, crude fibre and its components, starch, sugars, and ash was carried out on preserved samples from all plots. Biomass composition of the main four species (with cultivar results pooled) is shown in Table 12. The largest species difference was that sunflower had higher % fat and crude protein than other species.

Table 12: Biomass composition for four crop species (the mean of multiple cultivars within some species). JA = Jerusalem artichoke.

Attribute	Maize		Sorghum		Sunflower	JA
	Kerikeri	Flaxmere	Kerikeri	Flaxmere	Flaxmere	Kerikeri
% Crude Protein	5.1	7.2	4.2	6.4	11.8	4.7
% Fat	1.9	1.4	1.2	1.2	8.1	0.7
% Sugars	4.2	1.4	13.2	6.6	3.5	5.0
% Starch	20.1	13.1	1.1	1.3	0.4	0.3
% Cellulose	24.5	26.2	28.7	31.5	20.5	27.7
% Hemicellulose	27.0	30.4	23.0	24.0	10.2	12.6
% Crude Fibre	24.8	26.0	31.2	33.2	24.9	32.3
% NDF	54.9	40.0	57.1	60.6	36.9	48.0
% ADF	27.9	19.7	34.0	36.7	26.7	35.5
% Lignin	3.4	2.2	5.3	5.2	6.2	7.8
% Ash	3.4	4.8	4.8	6.2	12.2	8.8
% N	0.81	0.76	0.68	1.03	1.89	0.74
% DM	39.5	30.7	25.5	35.0	36.0	28.2

The procedure we used to calculate methane yield from the composition results was described in part in the Methods Section 2.5 and in detail in Kerckhoffs *et al*. (2011).

Our composition measurements (Table 12) were used to estimate methane yield by looking up crops with a similar chemical composition in a European database and finding how much methane they had produced in actual tests. We noted that crops from the screening trials had a similar chemical composition to those with similar maturity (as assessed by DM%) in the database, therefore the CE% for the New Zealand crops was calculated as the mean CE% of the 10 records closest in %DM to each of our samples. The maximum (Buswell) yield (Buswell and Müller, 1952) is shown as 'Max. yield potential (l_N $kg^{-1}VS$)' in Table 13. The methane volume is in pressure-normalised litres (l_N).

The actual specific methane yield was then calculated by multiplying the Buswell value by the CE% to estimate actual methane yield on a tissue basis (Table 13). Since the inorganic fraction of the DM or total solids (the ash content) is not digestible, the remaining part is the DM minus the ash. It is termed the volatile solids (VS) and the specific methane yield is generally expressed on that basis (l_N $kg^{-1}VS$).

To express the methane yield per ha, the specific methane yield (l_N $kg^{-1}VS$) was multiplied by the yield of VS ha^{-1}. The conversion factor for the methane yields to diesel equivalent is 0.944 (NZ Energy Data File, 2011). To express the yields in units of energy the conversion factor is 37.7 MJ m^{-3} (NZ Energy Data File, 2011). The conversion from gross to net energy yield is presented in Section 3.7.

There was no data available for JA in the EU-AGRO-BIOGAS Forum database (BOKU, 2010); therefore it was not possible to estimate methane production for this crop. This was measured in the BOKU laboratory following the Year 2 experiments designed to test the CLN concept with JA and sorghum.

The calculated specific methane yields for the screening trial biomass species were within the range reported in the literature. After Year 2 we were able to compare these to direct lab measurements on our new samples (Table 14 in Section 3.6).

Table 13: Methane yield parameters for the Year 1 biomass feedstock crops. Yield potential was calculated from Buswell and Müller (1952); Convertible Energy from BOKU (2010); DM ha^{-1} from the screening trial results (see text for details).

Crop	Site	Max. yield potential (l_N $kg^{-1}VS$)	Convertible Energy (%)	Specific yield (l_N $kg^{-1}VS$)	Volatile solids (kg VS ha^{-1})	Total yield (m^3 CH_4 ha^{-1})
Maize	Kerikeri	449	69	310	28802	8928
Maize	Flaxmere	440	69	304	12026	3651
Sorghum	Kerikeri	418	70	293	23720	6946
Sorghum	Flaxmere	427	71	303	14425	4377
Sunflower	Flaxmere	374	68	255	7112	1815

3.6 MEASURING METHANE PRODUCTION

3.6.1 Ensiling of samples

The ensiling methodology was successful, based on feedback from the BOKU laboratory in Vienna. Ensiled samples from the Year 2 experiments arrived in good condition and generated appropriate-ranging yields of biogas and methane.

3.6.2 Laboratory direct measurement

This procedure was performed in laboratory-scale digesters in the BOKU laboratory in Vienna during the first part of Year 3 (August to December 2011) as detailed in Section 2.5 and Appendix 2. The results from the measurements are shown in Table 14.

Table 14: Biogas and specific methane yields (direct laboratory measurement) during digestion of ensiled samples (Year 2) measured at the BOKU, Vienna. The standard deviations (SD) among 6 replicates are shown after each mean.

Crop Species & Cultivar	Biogas yield (l_N kg^{-1}VS)	CH_4 yield (l_N kg^{-1}VS)
Jerusalem artichoke		
'*Inulinz*'	392 (26.6)	254 (15.4)
Sorghum		
'*Sugargraze*'	544 (47.5)	332 (33.4)
Sorghum		
'*Jumbo*'	535 (49.4)	335 (34.1)

The direct biogas and methane measurements support the previous method of calculation using the Year 1 tissue composition. Sorghum methane yields were in fact about 10% higher in Year 2 than calculated in Year 1. The Jerusalem artichoke specific methane yield was almost the same as the value calculated for sunflower in Year 1.

The specific methane yields in the BOKU analyses were applied to the biomass yields in that 2010-11 Hawke's Bay experiment (Table 6) in order to quantify the total methane yield potential per ha (Table 15). DM yield was the most influential factor in gas yield, which favoured sorghum (*Jumbo*). If the JA DM yield potential (measured in a separate Year 3 trial, see Section 3.3) is taken into account with DM yield 1.9 times what we observed in the 2011 trials, then JA may produce methane yields in the range between the two sorghum cultivars in Table 15).

Table 15: Total yield of methane (m^3 CH_4 ha^{-1}) for the three crop cultivars (one JA and two sorghum cultivars) tested in the '*virtual CLN*' experiment. Volatile solids (the biomass fraction that can be converted to methane) equal DM minus ash. Total CH_4 yield = specific methane x tVS ha^{-1}.

Crop Species Cultivar	Specific Methane (m^3 tVS $^{-1}$)	Dry Mass (tDM ha^{-1})	% Ash	%Volatile Solids	Vol. Solids (tVS ha^{-1})	Total yield (m^3 CH_4 ha^{-1})
J.Artichoke '*Inulinz*'	254	16.3	11.3	88.7	14.5	3672
Sorghum '*Sugargraze*'	332	22.1	10.6	89.4	19.8	6559
Sorghum '*Jumbo*'	335	27	10.6	89.5	24.2	8091

If the CLN biomass production system is to be put into practice in New Zealand, it will be very helpful to quantify the methane energy value in the feed stocks going into the digesters. A laboratory facility such as at BOKU could be set up for direct methane measurement. Ultimately research will be necessary to calibrate a model that uses cost effective composition analysis from such measurement technologies as NIR for calculating methane production commercially (such as from a mix of feedstock species).

3.7 ENVIRONMENTAL BENEFITS OF FOSSIL FUEL SUBSTITUTION

3.7.1 Calculation of fossil transport fuel substitution per hectare

The ultimate aim of the CLN system is to increase sustainability of New Zealand agriculture by replacement of fossil fuels used in farming with renewable methane and by recycling N to replace fossil-fuel-derived synthetic fertiliser. To quantify fuel substitution precisely requires calculating the net fuel energy yield of the CLN system, which can be formally done using a Life Cycle Assessment (LCA). Stewart (1983) took a similar approach to an LCA to analyse the production of methane from crop-grown biomass in New Zealand. It indicated that the required energy inputs to grow the crops equalled about 5% of the gross energy return (Stewart, 1983; D.J. Stewart, personal comm.). In addition it required another 25% of the gross energy return to operate the digester and purify the biogas into compressed bio-methane (Stewart, 1983). This value falls within the broad range of energy input requirements determined by Börjesson *et al*. (2010) in a report evaluating various '*biogas crop to transport fuel*' pathways in Sweden.

Therefore the net energy yield from the three crops (the middle column in Table 16) equals 70% of the total yield (gross energy). We would like to reiterate that this approach of calculating a net energy yield is rather different to a financial analysis of the system, since the parasitic energy consumption is in reality a rather coherent block, including energy forms as diverse as transport fuel, electricity and waste heat.

The final column in Table 16 lists the diesel fuel equivalent of the net methane yield per hectare, using a conversion factor of 0.944 litres of diesel per cubic meter of methane. (NZ Energy Data File, 2011).

Table 16: Net energy yield from the three crops, as methane volume and diesel fuel energy equivalent.

Crop Species Cultivar	Total yield (m^3 CH_4 ha^{-1})	Net yield (m^3 CH_4 ha^{-1})	Diesel equivalent (l ha^{-1})
J. Artichoke *'Inulinz'*	3672	2571	2427
Sorghum *'Sugargraze'*	6559	4592	4334
Sorghum *'Jumbo'*	8091	5664	5346

The gross yields from the data in Table 16 for *Jumbo* sorghum (8091 m^3 CH_4 ha^{-1}) equals 295 GJ ha^{-1} (NZ Energy Data File, 2011). The net fuel energy produced in the '*crops to transport fuel*' chain is about 206 GJ ha^{-1}. The table shows this to be 5346 m^3 ha^{-1} in diesel fuel equivalent terms. The environmental benefit of substituting for diesel the biomethane produced by *Jumbo* sorghum biomass from one ha is equivalent to 14.5 t CO_2 yr^{-1}.

That value for GHG reduction per ha of sorghum cannot be projected to all of the 5% of marginal land in our mapping/modelling analysis; it would give a total reduction of 3.4M tCO_2. That more conservative analysis (see Section 3.10) calculated energy production equal to 595M litres of diesel, which at 73.25 kt PJ^{-1} equals a GHG emission reduction of 1.57M tCO_2. However, these benefits could easily be doubled by New Zealand farmers planting a second 5% of their marginal sites to biomass crops for methane fuel.

One further comparison, of interest mainly to energy engineers, is how the relative required energy inputs for a '*crops to biofuel*' system (up to 30%) compares with the inputs required to produce finished petroleum products. To carry out a LCA is beyond the scope of this paper, so the comparison will be made to literature findings. A USA report by Cleveland (2005) indicates 10% to 17% parasitic energy consumption (i.e. energy-requiring inputs) for finished petroleum products, while Szklo and Schaeffer (2007) estimate the parasitic energy consumption of the petroleum refining process alone to be between 7% and 15%. Although this comparison may indicate an advantage of petroleum fuels, it has to be considered parasitic energy consumption for producing the biofuel is increasing overall energy availability, whereas the parasitic energy consumption of the refining process diminishes a finite supply of non-renewal oil deposits.

It appears that a CLN biogas transport fuel production system will have a very positive renewable energy return on energy invested (a ratio exceeding 3) now, and future system refinements can help to improve this ratio further. Contrary, the parasitic energy consumption of petroleum fuels is going to increase going forward as ever more difficult petroleum deposits (tar sands, heavy oil) are going to make up an increasing share of the world oil supply.

3.7.2 Calculation of N fertiliser manufacture fossil fuel substitution per hectare

The fossil energy required for N fertiliser (that can be saved each year) is 11.4 GJ ha^{-1} for the 200 kg N ha^{-1} rate used in the sorghum trials (West and Marland, 2002), or 302 m^3 methane ha^{-1}. The energy saving is proportional to the N fertiliser required to replace the N removed in the crop or lost, so it also differs between crops.

3.8 PHENOLOGY MEASUREMENTS OF SORGHUM AND JERUSALEM ARTICHOKE

Sorghum phenology in the original APSIM model (Keating *et al*., 2003) matched well with phenology observed in Kerikeri (Table 18 in section 3.9). This is probably because the latitude of Kerikeri is closer to the Australian latitudes where the APSIM model was developed, compared with Hastings, which is further south.

For Hastings the original APSIM model better explained the observed phenology than the '*improved*' model, but for Flaxmere the '*improved*' model fitted better. However the reason for the poorer fit may have been because we did not have actual weather data for the Flaxmere site so we used Hastings data. Therefore, whilst the '*improved*' model may have predicted yield better than the original model, it generally did a poorer job of predicting the phenology. For JA phenology was also recorded (Table 17), but unfortunately there was no model predictions available by APSIM.

Table 17: Phenology measurements and cumulative growing degree days (GDD) using a base temperature 0°C for Jerusalem artichoke, grown at Hastings and Kerikeri. Leaf counts on main stem only.

Hastings 2010-11	Planting date	Emergence date	Leaf # 17 Jan	Leaf # 3 Feb	Leaf # 1 March	Flowering date
Data	9 Nov	25 Nov	40.3	53.9	74.5	23 Mar
GDD	0	247	1205	1525	2029	2395
Kerikeri 2009-10	Planting date	Emergence date	Leaf # 8 Jan	Leaf # 3 Feb	Leaf # 4 March	Flowering date
Data	4 Nov	19 Nov	35		66	14 Mar
GDD	0	232	1146		2267	2451

3.9 MAPPING '*MARGINAL*' SITES

3.9.1 Predicting the average maximum DM yield for sorghum and Jerusalem artichoke

The input parameters used to run the model to predict average maximum DM yield are given in Appendix 4. By comparing yields predicted by the original (as received) APSIM model with yields of sorghum grown at Flaxmere, Kerikeri and Hastings it was clear that the APSIM model underestimated sorghum yields by approximately one-third (Table 18). Changes were made to the APSIM model, which greatly improved its yield predictions (see Appendix 4); however, predictions of the phenological stages were still poor.

Table 18: Observed and predicted yield parameters for sorghum for the three experimental sites. Predicted yields are from both the original and modified APSIM models (see text for details).

Flaxmere	Emergence	Number of leaves					Flowering	Yield
	date	7 Dec	14 Dec	5 Jan	28 Jan	1 Mar	date	tDM ha^{-1}
Observed	24 Nov	2.7	4.9	8.4	11.2	14.0	None	12.8-28.0 depending on soil depth
Predicted, original model	27 Nov	2.3	3.3	6.4	10.0	16.2	None	16.3 (deep soil)
Predicted, modified model	26 Nov	2.6	3.7	7.0	10.9	19	None	26.6 (deep soil)
Hastings		17 Jan	3 Feb	28 Feb	21 Apr	Flag leaf		
Observed	17 Dec	6.5	9.0	12.1	15.1	5 mar	c. 19 Apr	27.0
Predicted, original model	15 Dec	7.4	10.7	16.7	19.0	6 Mar	12 April	17.1
Predicted, modified model	15 Dec	7.8	11.4	18.7	19.0	1 Mar	28 Mar	27.1
Kerikeri		25 Nov	7 Dec	8 Jan				
Observed	12 Nov	3	5.3	10.7			None	30.0
Predicted, original model	12 Nov	2.7	5.1	10.7			24 Feb	20.4
Predicted, modified model	12 Nov	3.0	5.5	11.5			18 Feb	28.9

The average maximum potential yield for the areas chosen for mapping was determined using APSIM. For sorghum this was done using the modified sorghum model (as described above). APSIM simulations predicted an average maximum potential yield of 25.7 tDM ha^{-1} for Hawke's Bay and 27.3 tDM ha^{-1} in Gisborne. The reason why Gisborne had 6.2% higher yields than Hawke's Bay was primarily the 4.1% higher solar radiation.

For Jerusalem artichoke the average annual maximum yield was more difficult to estimate as there was no computer model developed for this crop and experimental data was scarce. Data from three experimental trials in Hawke's Bay indicated that the maximum shoot DM yields for Jerusalem artichoke was approximately 15.6 tDM ha-1 (15.1tDM ha^{-1}, *n=3*; 2009-2010 experiment at Hastings, 16.3 tDM ha^{-1}, *n=8*; 2010-1011 experiment at Hastings, 15.0 tDM ha^{-1}, *n=8*; Overall average: 15.6 tDM ha^{-1}).

However no data exists from which to estimate average maximum potential DM yields for JA grown in Gisborne. Therefore DM yield was estimated by using the APSIM model approach to simulate average maximum potential yield for sunflowers grown in each region. APSIM simulations indicated that sunflower would yield 3.7% more in Gisborne than in Hawke's Bay. Therefore the average maximum potential yield of JA in Gisborne was assumed to be 3.7% more than what was achieved in Hawke's Bay, i.e. 16.2 tDM ha^{-1}. As noted in section 3.3, a 2012 JA trial at the same field site yielded >30 tDM ha^{-1} in plots planted in early spring, so JA methane yields have the potential to equal those of sorghum.

3.9.2 Comparing the crop suitability coefficient for EWS against data from the Flaxmere field trial

The values of k for EWS estimated from APSIM (see appendix 3) were compared with the 2009-10 field trial data from Flaxmere where sorghum and sunflower were grown in land subject to moisture stress. The k values were calculated as follows. The LENZ layer predicts an average annual water stress in this area of 196 mm of rainfall. Subtracting the 45 mm stored in the soil (data from the FSL plant-available water layer) and the 25 mm of irrigation applied, this gives an effective water stress of 136 mm. An effective water stress of 136 mm was assigned a suitability score (k) 0.68 for sorghum and 0.48 for Jerusalem artichoke (based on simulations for sunflower). When comparing the APSIM model predictions with actual field data, the model predicts a sorghum yield of 19.1 tDM ha^{-1} with the 2009-10 rainfall plus 25 mm of irrigation assuming 45 mm of water stored in the soil, as the LENZ map predicted, which is 0.70 of maximum simulated yield of 27.2 tDM ha^{-1} with the same weather data-set plus irrigation. Actual field data measured the soil water holding capacity at the water monitoring site of 38 mm, although there was a large degree of variation among plots. The highest yielding sorghum plot (*Jumbo*; replicate 3) yielded 28 tDM ha^{-1}, which was close to our maximum yield of 27.2 tDM ha^{-1} predicted by APSIM. The other two plots averaged 16.9 tDM ha^{-1}, which is 0.62 of maximum yield at this site (see Table 19).

For sunflower, replicate 3 again produced the maximum yield of 12.3 tDM ha^{-1}, with the other two replicates producing 6 tDM ha^{-1}, which is 0.49 of maximum yield. However APSIM underestimated maximum yield of sunflower (10.4 tDM ha^{-1}) and overestimated the yield in the presence of water stress, assuming we could still grow 0.80 of maximum yield (Table 19). JA may not be as severely affected by water deficit as sunflower. In the 2012 trial in a shallow (marginal) soil an early season water deficit (soil water deficit not quantified) led to continuous wilting of JA plants be late January. Plants were harvested and had a yield of 13.4 tDM ha^{-1} Having a JA crop model would be preferable to having to equate the species to sunflower.

Table 19: Comparing the actual effect of 136 mm of water stress with the effects predicted by the crop suitability coefficient and by the APSIM model. All values are presented relative to the maximum yield for that area in that season.

Crop	k value for 136 mm	Yield predicted by APSIM (relative to maximum)	Observed yield (relative to maximum)
Sorghum	0.68	0.70	0.62
Sunflower*	0.48	0.80	0.49

* A substitute for JA, since JA was not grown in Flaxmere nor has a model been developed for this crop in APSIM.

3.9.3 Map of land suitability for biofuel crops

The map showing the suitability of land in Hawke's Bay for sorghum (Figure 6) shows the built up areas of Napier and Hastings that are not suitable for biofuel cropping. It also shows a considerable amount of land around these cities that is shaded white. This land is in short rotation cropland and therefore not considered marginal land. The white coloured land northwest of Hastings is in vineyards and therefore also not considered marginal land. The irregular shapes of '*white shaded*' land in Figure 6 surrounding the Heretaunga plains is steep land that is not suitable for cropping. The crop suitability coefficients of the coloured land (potentially suitable for biofuel crops) indicate that yields will decline towards the centre of the Heretaunga Plains. This is mostly because the effective water stress (EWS) increases towards the centre of the Plains. Certainly the rainfall declines towards the centre of the Heretaunga Plains, but the decline in EWS is also affected by soil type, and we see that land located near the Hastings site, which had a deep soil that stores a lot of plant-available water, is coloured orange indicating it has a high crop suitability coefficient for sorghum production and should achieve near maximum yields.

In contrast land near the Flaxmere site stored a low amount of plant-available water, and so is classified with a much lower crop suitability coefficient for sorghum, and will only yield approximately 60% of maximum yield in an '*average*' year. Maps of suitability for sorghum for other regions, and maps for Jerusalem artichoke are provided in Appendix 6: Figures A-E.

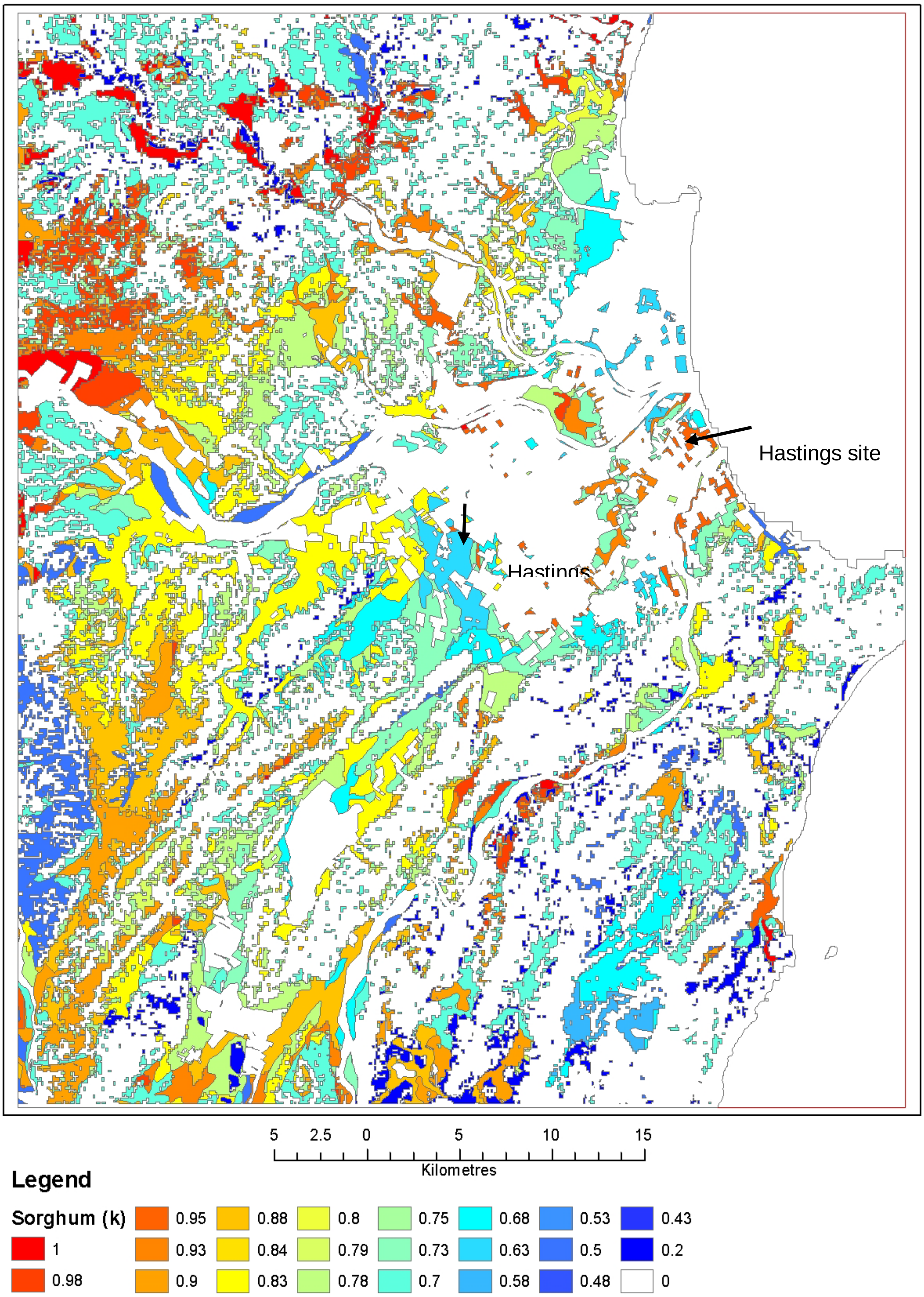

Figure 6: Map of Heretaunga plains and surrounds showing the suitability of land for sorghum. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for sorghum of 1 is estimated to yield 25.7 tDM ha^{-1} in an average year. Land with k=0.98 is assumed to yield 0.98 × 25.7 = 25.2 tDM ha^{-1} in an average year.

3.10 THE POTENTIAL OF BIOFUEL CROPS TO SUPPLY NZ RURAL FUEL REQUIREMENTS

The potential biomass yields for each region, as estimated by APSIM and then reduced by 25% to allow for compaction, pests and disease and other limitations are given in Table 20. This method may provide very conservative yields for JA, since it is starting with the low APSIM sunflower yield. The potentially over-conservative values were however used for reasons of consistency. We then assume that only 5% of the marginal land in each region is planted in a biofuel crop (see Table 20).

Table 20 shows that the total potential biomass from marginal land is over 77M tDM; 5% of this land will therefore yield about 3.9m tDM yr^{-1}. A calculation of methane gas yield from this biomass uses the specific methane yield, as in Table 15. This is expressed in units of m^3 tVS^{-1}, where VS is volatile solids. A conservative factor of 89% has been used to convert total DM to VS, based on the highest ash content of 11%, re-coded during our trials (see Table 11) The tonnage of VS on 5% of the land is therefore 3.5M tVS. Assuming a further 10% loss of biomass in the process of transportation, silage making and loading into the digester this becomes 3.1M tVS.

The specific methane yield from sorghum is about 330 m^3 tVS^{-1} but only 255 for JA and 335 m^3 tVS^{-1} for lucerne (Amon *et al*., 2007a). Simplifying to a single value of 290 m^3 tVS^{-1} the calculated total methane production, the resulting net figure is 900 million m^3 of methane from 5% of the marginal land based on summer dryness.

Using conservative numbers, around 30% of the gross biogas energy produced is required to operate the entire biogas crop to fuel system (Stewart, 1983; Börjesson *et al*., 2010). To calculate the total available net energy, parasitic energy consumption of 30% is therefore deducted from the gross energy yield of 900M m^3 methane yr^{-1}, resulting in 630M m^3methane yr^{-1} available net energy. The conversion to diesel equivalent equals 595M litres. The 630 M m^3 methane yr^{-1} have an energy content of 21.4 PJ, which represents 160 % of the diesel fuel used by the Agriculture, Fishing and Forestry Sector in 2010 (13.3PJ; NZ Energy Data File, 2011). The associated environmental benefit of this fossil fuel energy substitution (see Section 3.7) is for a reduction in GHG emissions of 1.57M tCO_2.

Table 20: Estimated biomass and methane production off arable land from different summer dry regions in New Zealand. Estimated yields are 75% of those modelled by APSIM. Sorghum followed by winter wheat were grown in areas from Hastings northwards, and lucerne to the south.

LENZ environment label	Area descriptor	Representative weather station	Area (ha)	Water deficit (mm yr^{-1})	Solar radiation (MJ m^{-2})	Annual temp. (°C)	Slope (Degrees)	Estimated yields (tDM ha^{-1})	DM produced (t)
A1-3	North Cape	Kaitaia on a sandy soil	82393	103-121	15.3	15.7-15.8	1.2-5.5	23.2	1909643
A4-A5, G1	Northland and northern coastal sands	Kaitaia on a silt loam	500894	51-85	14.9-15.1	14.3-15.3	0.6-2.5	26.6	13307000
B1-B5, B7	Central dry lowlands	Hastings	557772	62-181	14.3-15.2	10.7-13.3	1.2-9.0		15712856
B6,B9	Marlborough	Blenheim on sandy soil	48134	248-261	14.9	12.2-12.4	2.1-3.9	10.5	507429
C3, F4, I2	Central Wairarapa, Southern Hawke's Bay	Masterton	731089	93-107	14.0-14.2	12.2-12.7	0.6-7.9	16.1	11777295
I3-I6, J2	Central poorly drained soils, Marlborough well drained soils	Blenheim on sandy loam	188697	182-225	14.1-14.8	11.3-13.8	0.2-2.9	12.2	2310783
J1, 3,4	Marlborough and lower Nth Island river valleys	Blenheim on a silt loam	180485	97-130	14.2-15.3	12.0-12.7	0.9-1.8	14.0	2517766
L1, L2,L4	Southern Sth Island lowlands	Gore on a sandy soil	625705	54-114	12.4-12.6	9.8-10.5	0.4-2.8	16.1	10062744
N1	Canterbury Plains	Lincoln	404783	183	14	11.3	0.7	13.4	5441194
N2-N3	Inland Canterbury Plains, Sth Canterbury, Otago Plains	Timaru	1092973	82-113	13.0-13.6	9.5-10.5	0.3-4.2	10.9	11925428
N5-N7	Ranfurly, Wanaka, Upper Waitaki, eastern Central Otago	Lauder	273650	194-238	13.6-13.8	9.1-9.2	0.2-1.6	5.9	1609678
N8	Alexandra, Cromwell to Luggate	Clyde	39141	307	13.9	10.2	2.3	4.3	167621
Total biomass production (tDM) from arable land in New Zealand with >50mm annual water stress (marginal land)									77249438
5% of total biomass production (tDM)									3862472
Methane production from 5% of marginal arable land (m^3 CH_4 × 1,000,000)									1160

3.11 ECONOMIC FEASIBILITY

Determining an accurate costing of production for biogas from a CLN-type of scheme is rather difficult, as the cost will be very case specific. While economies of scale for digestion equipment would favour large digestion facilities, logistic costs for digester feedstock and digestate, the limited demand for energy in relatively sparsely populated rural regions and the organisational overhead associated with bigger plants provide justification for the use of more modest sized CLN biogas schemes under NZ conditions.

For the CLN workshop in Taupo (held at 19 June 2012; see program in Appendix 7) a NZ scenario modelled on the Margarethen am Moos (see Appendix 9) co-operative biogas scheme near Vienna (Austria) was developed to showcase, albeit rather basic, some specific financial data of the CLN system. Analogous to the Austrian example, our NZ scenario envisaged a group of 12 farmers in the Lake Taupo area producing ~ 5,100 t (VS) biomass grown on 220 ha of land.

The crop rotation was envisaged to consist of 90 ha of Jerusalem artichoke, 80 ha of triticale whole crop silage, 30 ha of sorghum and 20 ha of maize. In conjunction with triticale, sorghum and maize a winter legume, i.e. crimson clover (or tickbeans) is grown, on a total are of 130ha.

The cost of production (see Table 21) was projected for each feedstock based on data from KTBL (1999) and the KTBL (2012a) online database. The cost of feedstock production includes all variable cost of production (including seed, herbicide and the like), variable machinery cost (including the cost of digestate application, and feedstock transport to a silage stack adjacent to the biogas plant), as well as levied fixed machinery costs. The cost calculation does include a land rental of 300$ ha^{-1}, but does not include a grower profit. Furthermore average feedstock and digestate transport distances are assumed to be around10 km. To convert the cost of feedstock production to methane, the measured VS to methane conversion rates from Tables 13 and 14 have been used for maize, sorghum and JA. Conversion factors for triticale and the intercrop crimson clover (proxy, clover grass mix and lucerne, both 0.335 m^3CH_4 $kg^{-1}VS$) were taken from Amon *et al.*, 2007b.

Table 21: Cost of feedstock production for the Lake Taupo scenario. Biogas feed stock production is modelled on a farmer group using 220 ha of land for bioenergy production.

	Area	VS yield	VS total	Produc-tion cost	Methane yield	Methane yield	Contribution	Cost
	ha	$t\ ha^{-1}\ y^{-1}$	$t\ y^{-1}$	$ t^{-1} VS	$m^3CH_4ha^{-1}y^{-1}$	$m^3\ CH_4y^{-1}$	%CH4 yield	$ $m^{-3}CH_4$
JA	90	20.0	1,800	$ 112.73	5,080	457,200	31%	$ 0.44
Triticale	80	16.0	1,280	$ 144.18	4,240	339,200	23%	$ 0.54
Sorghum	30	20.0	600	$ 188.62	6,640	199,200	13%	$ 0.57
Maize	20	22.0	440	$ 143.02	8,756	175,120	12%	$ 0.36
Intercrop Crimson)	130	7.5	975	$ 106.98	2,513	326,625	22%	$ 0.32
Total	220/ 350		5,095			1,497,345	100%	
Average		23.2		$ 131.08	6,806			$ 0.45

The cost of production for JA biomass is below average, mainly as a consequence of the crop being a perennial, with limited crop care needs. The intercrop crimson clover also has a lower cost of production due to reduced crop care needs as well as the land rental being covered by the main crop. The average cost of production ($131 t^{-1} VS = 13.1 cents kg^{-1} VS) is generally in line with maize silage being sold e.g. in the Waikato for 10 cents kg^{-1} DM (good year) to 16 cents kg^{-1} DM (dry year). The cost comparison to maize silage does however include a grower profit but generally not the cost of harvesting, and particularly not the cost of (often long distance) cartage of maize. The weighted average production cost of $0.45 $m^{-3}CH_4$, based on the feedstock cost given in Table 21, equates to a feedstock cost of 13.12$ GJ^{-1}.

To realize the annual yield of biogas, 2,6M m^3 yr^{-1}, containing 1.49M m^3 of methane, from the feedstock, a digester facility with a 3,500 m^3 main fermenter would be required.

CAPEX and OPEX costs for a 3,500 m^3 fermenter facility were taken from the KTBL (2012b) online database in Germany, based on several thousand biogas plants operational on farms. The capital costs included the digester, and digestate storage facility, biogas upgrading plant, gas compressor/refuelling facility and controls. The total cost was projected as NZ$1.9M. Since different part of the biogas facility will have a different useful equipment live (between 5 and 20 years) the annualized investment cost for the biogas plant were projected as NZ$ 181,000 $year^{-1}$(Table 22).

Table 22: Cost of converting biogas feedstock into upgraded bio-methane modelled for the Lake Taupo scenario.

	Physical production		Total cost	cost per m^3CH_4	cost per GJ
			$ y^{-1}	$ $m^{-3}CH_4$	$ GJ^{-1}
Biogas plant annual VS input	5,095	tVS y^{-1}			
Biogas plant annual raw CH4 production	1,497,345	m^3 CH_4 y^{-1}			
Raw material cost			667,869.36	$ 0.45	$ 13.12
Annualized investment cost biogas plant			181,167.45	$ 0.12	$ 3.56
Annual interest cots biogas plant (9%)			85,734.03	$ 0.06	$ 1.68
Cost of plant operation			106,312.78	$ 0.07	$ 2.09
Sub total			*1,041,083.63*	*$ 0.70*	*$ 20.45*
Parasitic heat use (over heat recovery) 10% of total gas	149,735	m^3CH_4 y^{-1}	104,108.36		
Net (purified) methane available (*total*)	1,347,611	m^3CH_4 y^{-1}	1,145,191.99		
Net (purified) methane cost of production (*average*)				$ 0.85	$ 24.99

Annual interest costs ($86,000 $year^{-1}$) assumed repayment of the facility components over its useful life and an interest rate of 9%. Plant operating costs include consumables, plus all electrical energy for pumps, stirrers and compressors, but not the digester heat requirements that cannot be met with recovered waste heat. It was therefore conservatively assumed that in addition to recovered waste heat 10% of the plant biogas output would be consumed internally for heating at the marginal cost of production, reducing the overall volume of methane available for high value uses such as transport fuel to1.3M m^3CH_4 $year^{-1}$ (Table 22).

Using this simplified approach the cost of renewable methane production, including the cost of feed stock provision following the CLN approach plus the levied CAPEX and OPEX cost of a plant required to digest the feedstock and purified and compress the fuel fit for use in a gas powered vehicle, can be calculated as 25$ GJ^{-1}.

In energy terms the Lake Taupo scenario would yield 45,000 GJ y^{-1} gaseous fuel with an energy equivalent to 1.27M L diesel fuel. At a retail diesel price of 1.50$ L^{-1} the energy equivalent diesel cost is 42$ GJ^{-1}. We are confident that for some applications the difference between 25$ GJ^{-1} for biogas methane and 42$ GJ^{-1} for diesel can justify the conversion cost and impracticalities associated with the operation of gas powered vehicles. With petroleum cost increases in the future, it is also likely that the financial attractiveness of biogas vehicle fuel is going to increase, broadening the scope for application further.

A simplified financial analysis as provided above cannot outline the economic implications of a CLN biogas plant to the degree necessary to make an investment decision. This simplified analysis merely sought to provide an overview, indicating that a CLN biogas system, based on cropping marginal agricultural land can make sense in terms of conventional economics and the given energy costs and technologies available today.

In terms of rural benefits of a new industry producing fuel from crops and crop residues methane production has a lot to offer. The example of the facility outside Vienna (Austria) included also waste handling (manure) from a piggery, 625 kW electricity generation, waste heat fed into a district heating plant that served half of the nearby village, a vehicle fuel station for local transport plus the farm's two 200hp tractors (see Appendix 9).

In Germany, with over 7000 farm biogas plants in place from an agricultural land base not much larger than that of New Zealand, it is clear that the fuel and other energy produced is enough that it would have a large benefit if applied to the rural sector. In actual fact, due to the German government feed-in-tariff requiring power companies to pay a high price for renewable energy during the next few years, the main benefit to farms is financial. They use most raw biogas to generate electricity to sell or they upgrade it to methane to sell into the gas grid.

Appendix 8 is summarising some frequently-asked-questions (FAQs) raised at the organised workshops and through other interactions with stakeholders and interested parties. They are dealing with perceived risks and feasibility around the possible application of biogas in NZ.

4 Conclusions

Given the short time-span of the project it was known at the outset that it would not be possible to set up a working CLN scheme in which biomass was produced, put into a digester to extract biogas, with digestate reapplied to the next year's CLN rotation crop in order to measure plant growth under closed loop nitrogen conditions. The objectives therefore aimed to assess a '*virtual*' CLN system constructed from the results of the system component tests. While this is not the same as doing a full test, the links between the components have been fully demonstrated by a research network in Europe, The EU AGROBIOGAS NETWORK, with a data base of methane production containing thousands of crop analyses. In addition, thousands of commercial facilities have demonstrated the ability to produce biogas and fertilise biomass crops with digestate.

The first component test was the biomass yield attainable by the crop species. Sorghum had shown very high DM yield ability in the Year 1 screening trial in Kerikeri, with the best two cultivars (*Sugargraze* and *Jumbo*) yielding 27 and 30 tDM ha^{-1} respectively. The high sorghum yield was confirmed in the Year 2 trial in Hawke's Bay. Sorghum also was the highest yielding crop in the drought-affected field trial at Flaxmere. While the Jerusalem artichoke above-ground DM yield was lower (16 tDM ha^{-1}), a new trial at the same experimental site in the 2011-12 season tested first-year plantings sown at the same mid-spring time as in the Year 2 CLN trial plus a very early sowing date. The latter yielded 1.9 times the DM of the 2011 harvest. The 2010 trial did find JA yield to be more reduced by water deficit than for sorghum, but a 2012 result in a marginal (shallow soil) site following a drought had a much higher yield than used in our model analyses. The new JA results suggest that high biomass is attainable throughout New Zealand, not just in the warmer regions north of Hawke's Bay. Yields of both species are higher than reported in most temperate climates, presumably due to the longer season with milder winters in New Zealand. The winter legume yields in the system with sorghum are, in particular, very superior to those in North America and Europe (other than the warmest Mediterranean climatic zones).

The second component test was the ability to fertilise a biomass crop with nutrients recycled to the land in the biogas digestate. The results of our trial with sorghum affirmed this capability – there was no significant difference in sorghum biomass yield between plots fertilised with digestate or with ammonium at both fertiliser rates.

The third component test of the '*virtual*' CLN system was the biogas and methane yield per unit of biomass. Results from the Vienna laboratory where methane was measured from our samples directly showed that the gas yields were at least as high as those estimated by the method used with the tissue samples from the Year 1 screening trials. Yields were also very much in line with those from biomass crops grown and tested in Europe.

Using the measured methane productivity factors to construct a New Zealand scenario of a 3,500 m3 digester scheme, based on 220 ha of CLN cropping land, showed an impressive methane yield of 45,800 GJ yr^{-1}, energy equivalent to 1.27 M L diesel yr^{-1}. Basic financial analysis of this scenario indicated that upgraded bio-methane from a CLN cropping scheme can be produced for less than the retail price for diesel, providing a cost spread that can justify the higher investment cost and impracticality issues around gas powered vehicles.

In terms of relative rural benefits from various potential new industries, producing methane fuel from crops (and crop residues) has a lot to offer. The scale of calculated biogas potential from only 5% of the '*marginal*' land sites in NZ has been projected to be ~ 900M m^3 of methane yr^{-1} gross, with a net yield of 630 M m^3 methane yr^{-1}, once parasitic energy consumption has been subtracted. If this can be realised and the fuel, heat and power put to use in rural New Zealand the result would be an important new addition to the rural economy.

The farming side of this type of biofuel production is the sustainable cropping system.

The aim of this project was to provide a proof of concept for the CLN cropping system as a new use for marginal land. This has been achieved in terms of testing all system components. Once a digester is available it would be possible to fully test a CLN cropping system and to compare New Zealand results to those in Europe. A successful CLN cropping system will achieve the aim of the SLMACC programme.

The substitution of a considerable quantity of fossil fuel (and a lesser quantity of natural gas used in N fertiliser production) with a high value biofuel produced on marginal land is a very practical adaptive strategy to the challenges posed by climate change and fossil fuel depletion. The diesel fuel substitution alone would save GHG emissions equal to 1.73 M tCO_2 yr^{-1}, and reduce New Zealand's overall agricultural GHG emission budget by a considerable amount.

The CLN scheme could also improve the export marketing position of the rural sector by reducing the GHG footprint, while at the same time offering fuel security benefits and more predictable energy prices.

5 Recommendations

(1) Given how significant these findings potentially are to NZ agriculture in the near future they should be carefully reviewed and information on this opportunity to reduce the farming carbon footprint supplied to the rural sector, both farming and transport.

(2) We believe that a major barrier to uptake of this '*green*' fuel technology in NZ is lack of profile, technical information and especially demonstration biogas plants using crops. By combining capacities of the private sector, research and NZ government, a commercial scale pilot plant could be built as a follow-up project. Such a plant could act as a reference point and as a pilot project for various trails for the energetic utilization of energy crops, wastes and by-products. This would then also enable full testing of the CLN cropping system.

(3) To close knowledge gaps regarding the financial aspects of a CLN biogas scheme, it would be valuable to commission a study of the potential macro and micro-economic benefit of a rural biomethane fuel sector. This assessment can include the use of orthodox economics, but certainly also ecological analyses that recognise the need for a shift to sustainable rural energy. The consequences of starkly increasing conventional fuel prices should be analysed as part of this study.

(4) Commercial laboratories that test crop tissue for feed quality should consider adding tests that are important in determining methane yield from AD with current arable crops; this would create a database to use in a NZ calibration of the Methane Energy Value Model used in Europe, to allow future cost effective tissue analysis by NIR as model input data.

(5) Follow-up biomass cropping trials with the recommended cultivars could be commissioned at sites around the country. A specific aim is to redefine the phenology of Jerusalem artichoke when planted early and define the effect of latitude on shoot/root partitioning.

6 Project Outputs

6.1 RESEARCH PAPERS (REFEREED)

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9 Appendices

Appendix 1: Structure of the program

This appendix describes the structure of the program with associated intermediate outcome, objectives and milestones.

Intermediate outcome: N efficient cropping systems

We aim to mitigate fossil fuel use in agriculture and in the manufacture of nitrogen (N) fertiliser, and thus contribute to MAF's Plan of Action, by defining and testing a novel energy crop production system that involves growing new non-woody crops in combination with legumes on marginal land to generate biomass that can be converted to biogas using anaerobic digestion technology. This will be achieved by assessing the capacity of novel crops with high N-use efficiency in combination with legumes to produce a self-sustaining biogas-producing system that does not require external N inputs (but will recycle the N in biogas plant digestate) and can be grown on marginal lands in New Zealand, where it does not compete with use of prime land for food production.

The key steps involve identifying optimal land use and novel crop/cultivar combinations (Objective 1), and developing crop production systems that feature closed loop N supply principles (Objective 2). Features of the closed loop N supply system and novel crop combinations, including improved genotypes, will be submitted to appropriate international journals or conferences.

By 2012 this concept of sustainably producing novel N-efficient biofuel crops on marginal land will have been fully developed, and the potential scale of GHG emission reductions from the adoption of this technology calculated. Knowledge of the practices and technologies involved will be disseminated and demonstrated to sector groups, regional investors and policy makers. By 2015, an industry/government partnership will be established and the technology fully evaluated, and by 2018 landowners and policy makers will have endorsed and implemented the technology.

Objective 1: Identify optimal land use and crop/cultivar combinations (Year 1)

A desktop study will define the (sub) classes of marginal land and serve as a basis for objective assessment of land use by region for new sustainable production systems for energy crops. The most promising combinations of new species/cultivar and legumes (as annual or perennial crop) for maximising biomass production will be assessed for use in these relevant subclasses of marginal land.

Milestone 1.1: Marginal land definition *(Year 1)*

Using existing land-classification methods develop a functional definition of (sub) classes of marginal land, and based on a literature study identify the most promising combinations of biomass species/cultivar and winter/perennial legumes as candidates for growing under the particular limitations in each relevant subclass of marginal land.

Objective 2: Design an energy crop production system with closed loop N supply (Year 1-3)

Design a novel energy crop production system featuring closed-loop N dynamics following the field screening of novel biomass production crops identified in the desktop assessment in objective 1 at two locations – Kerikeri and Hastings. Data on biomass produced, N required and phenology will enable the identification of at least two biomass crop combinations.

Closed-loop N dynamics will be analysed through measurements of bulk N taken from post-pastoral soil to gauge N requirements. These requirements will be met through the return of liquid digestate from an anaerobic digestion biogas plant. System specifications and performance will be communicated through industry field days or at workshops. A map of the biofuel potential of novel energy crop production systems for NZ's marginal lands will be constructed using modelling approaches of a `*virtual*' system with results reported to MAF and in papers to international journals or at conferences.

Milestone 2.1: Field screening of novel biomass production crops (Year 1)

Screen ten promising high biomass species/cultivars at two locations: Northland (Kerikeri) and Hawke’s Bay (Hastings). Measure the amount of biomass produced and the amount of N required by the various crops in order to optimise the N-inputs for each cropping sequence. Collect phenology data (e.g. leaf number, time to flower) on selected novel cultivars so that their growth can be modelled under the range of climatic conditions found in New Zealand. Grow a crop of maize to take up the bulk N from a post-pastoral soil, gauge N uptake, and calculate the N requirement of the subsequent energy crop (also using the amount of N fixed by the legumes).

Milestone 2.2: Closed loop nitrogen (N) system (Year 2)

In Y2 trial we will apply the identified amount of N to the energy crops in the form of liquid digestate from an AD biogas plant. Make phenology measurements for use in an energy crop performance model (milestone 2.3).

Milestone 2.3: Virtual system for novel energy crops for NZ marginal lands (Year 3)

Model potential energy crop performance in existing crop models using phenology data from milestone 2.2 in order to predict biomass yields for other marginal land classes throughout New Zealand. Full data analysis based on combination of experimental and model work will create a map of biofuel potential of the novel energy crop production system for NZ marginal lands. The full data analysis will use field data to calculate N balance and system N surplus. The DM yield plus modelled biogas yield will also be used to assess the system potential to replace fossil fuel, to mitigate GHG emissions and determine economic feasibility.

Appendix 2: The direct method to measure methane yield used at BOKU, Vienna

(1) *Determination of (organic) dry matter and ingredient composition.*

The chemical composition of the sample was determined by analysing the following compounds: total solids (DM), raw ash (XA), cellulose (CEL), hemicellulose (H-CEL), and lignin (ADL). To analyse the dry matter content, it was dried in a chamber at 105 °C until a constant weight was reached. The dried material was burned in a muffle furnace at 550 °C and used to determine the raw ash content. The volatile solids were calculated by subtracting the raw ash content from the total solids. Cellulose, hemicellulose and lignin were determined by using standard procedures. Hemicellulose can be calculated by determining the difference between neutral detergent fibre (NDF) and acid detergent fibre (ADF); cellulose can be calculated by determining the difference between ADF and acid detergent lignin (ADL). Moreover, the ash content was subtracted from the cellulose and hemicellulose content.

(2) *Specific methane yield according to VDI 4630.*

The specific methane production was measured in the laboratory using eudiometer-measuring cells under controlled fermentation conditions. Fermentation of different variants was done in triplicates. The analysed variants and the inoculum were weighed out in a ratio of 1:3 (based on DM). Inoculum was used from biogas plants Utzenaich (Upper Austria). Inoculum and substrates to be analysed were fermented for about 40 days in a eudiometer under anaerobic conditions and control of the pH value. A eudiometer contains six measuring cells. Each measuring cell consists of a gas manifold that is filled with sealing liquid. The top end of the manifold is coupled to a compensating vessel. The bottom end is connected with the fermentation tank that contains the sample material and the inoculum. A water bath maintained the temperature of the reaction vessels at 37,5°C. Biogas produced in the fermentation vessel displaced sealing liquid from the gas manifold into the compensating vessel. The specific biogas production was read off a column scale attached to the gas manifold and stated as gas standard volume. Every variant remained for about 40 days in the eudiometer for anaerobic fermentation. Over the course of these 40 days, produced biogas amounts and composition thereof were determined at first daily, then every two to four days. The portable gas analyser (Dräger X-am 7000) (accuracy of measurement ± 1-3 % of the reading) was used to determine the methane concentration (CH_4) of the biogas. The gas analyser was calibrated with test gas (60 % CH_4 and 40 % CO_2) prior to each measurement. The quasi-continuous measurements of methane concentrations were validated in periodic intervals by a gas chromatographically reference method. H_2S concentrations were measured simultaneously with methane concentrations in the headspace of the fermenter using the portable Dräger gas analyser respectively Dräger measurement tubes (0.2/A measuring range 0.2 - 7 Vol.%) for different measuring ranges. The accuracy of the measurement was ± 5-10 % of the reading. For the determination of the NH_3 concentration in biogas Dräger measurement tubes of the type 5/b 8101941 (measuring range 5-100 ppm) were used. The accuracy of the measurement was ± 10-15 % of the reading. The hydrogen content in biogas was also measured with the portable Dräger gas analyser. The measuring range of the electrochemical sensor ES encompassed 0 – 2000 ppm H_2. The accuracy of the measurement was ± 5% of the reading. The mentioned measurement parameters have been used to assess the fermentation progress and the stability of the fermentation processes. Those values have also been the basis for the calculation of specific biogas and methane yields of different variants.

(3) *Calculation of the specific methane yield.*

(a) Standard volume of gas. The standard volume of gas produced in discrete time periods was calculated for each eudiometer cell:

$$V_0^{tr} = V \cdot \frac{(p - p_w) \cdot T_0}{p_0 \cdot T} \qquad (1)$$

V_{0tr}	volume of dry gas at standard state, in mlN
V	volume of gas as read off, in ml
P	pressure of gas phase at time of reading, in hPa
p_w	vapor pressure of water as function of temperature of ambient space, in hPa
T_0	standard temperature; T0 = 273 K

p_0 standard pressure; p0 = 1013 hPa

T temperature of fermentation gas or ambient space, in K

(b) Composition of dry biogas. The composition of dry biogas produced in discrete time periods was calculated for each eudiometer cell. The concentrations of methane and biogas were analysed simultaneously.

$$C_{Korr.}^{tr} = C_{CH4} \cdot \frac{100}{C_{CH4} + C_{CO2}} \tag{2}$$

$C_{Korr.}^{tr}$ corrected concentration of biogas component in dry gas, in % by volume

C_{CH4} measured methane concentration in gas, in % by volume

C_{CO2} measured carbon dioxide concentration in gas, in % by volume

(c) Gas production by inoculum and corrected standard volume of gas. In order to calculate the gas production of sample material, the gas production by inoculum has to be subtracted from the standard volume of gas.

$$V_{IS(korr.)} = \frac{\Sigma V_{IS} \cdot m_{IS}}{m_M} \tag{3}$$

$V_{IS(korr.)}$ gas volume released from seeding sludge, in mlN

ΣV_{IS} total of gas volumes in test with seeding sludge for test duration under consideration, in mlN

mI_S mass of seeding sludge used for the mixture, in g

m_M mass of the seeding sludge used in control test, in g

(d) Specific biogas production of sample material. Biogas, produced in a certain period of time, in standard litre (IN) in relation to ignition loss mass of sample material, stated in $lN(kgVS)^{-1}$.

$$V_S = \frac{\Sigma V_n \cdot 10^4}{m \cdot DM \cdot VS} \tag{4}$$

V_S specific biogas production relative to ignition loss mass during test period, in lN/kgGV

ΣV_n net gas volume of substrate or reference substrate for test duration under consideration, in mlN

m mass of weighed-in substrate or reference substrate, in g

DM dry matter content of sample in % fresh matter

VS volatile solids of sample in % dry matter

(e) Specific methane production of sample material. To obtain the actual methane production of the sample material in relation to the weighed-in sample amount, the gas production of the inoculum has to be subtracted from the total volume produced.

(f) Cumulative biogas respectively methane production. Specific biogas respectively methane production volumes of sample material, calculated for single time periods, were cumulated. For graphic representation these values were plotted against test duration.

Appendix 3: Tables of values for the crop suitability co-efficient (k)

Table A: Effect of area of rocks on the crop suitability co-efficient (k).

This table shows areas of land considered available for biofuel cropping (1) or unsuitable (0). Land may be deemed unsuitable either because it is highly productive cropping land (and therefore cannot be considered 'marginal') or because it is not practical or socially acceptable to be sown in a biofuel crop. Descriptions based on Thompson *et al.,* 2003).

Description	k
Built-up area	0
Urban parkland/open space	0
Surface mine	0
Dump	0
Transport infrastructure	0
Coastal sand and gravel	0
River and lakeshore gravel and rock	0
Landslide	0
Alpine gravel and rock	0
Permanent snow and ice	0
Alpine grass-/herbfield	0
Lake and pond	0
River	0
Estuarine open water	0
Short rotation cropland	0
Vineyard	0
Orchard and other perennial crops	0
High producing exotic grassland	1
Low producing grassland	1
Tall tussock grassland	1
Depleted grassland	1
Herbaceous freshwater vegetation	0
Herbaceous saline vegetation	0
Flaxland	1
Fernland	1
Gorse and or broom	1
Manuka or kanuka	1
Matagouri	1
Broadleaved indigenous hardwoods	0
Sub alpine shrubland	0
Mixed exotic shrubland	1
Grey scrub	1
Shelterbelts	1
Afforestation (not imaged)	1

Afforestation (imaged, post LCDB 1)	1
Forest - harvested	1
Pine forest - open canopy	1
Pine forest - closed canopy	1
Other exotic forest	1
Deciduous hardwoods	1
Indigenous forest	0

The limitations used were area of rocks (Table B), gravel content (Table C), gravel size (Table D), slope (Table E), drainage (Table F), effect on growing degree days (Table G), effective water stress (Table H), salinity (Table I) and soil pH (Table J).

Table B: Effect of area of rocks on the crop suitability co-efficient (k).

Area of rocks (%)	Description	k
0	Non-rocky	1.0
0-1	Slightly rocky	0.9
2-9	Moderately rocky	0.5
10-24	Very rocky	0.2
25+	Extremely rocky	0.0

Table C: Effect of soil gravel content on the crop suitability co-efficient (k).

Gravel content (% Volume)	Description	k
<5	non-gravely to very slightly gravelly	1.00
5-15	slightly gravelly	0.84
15-35	moderately gravelly	0.70
35-70	very gravelly	0.50
>70	extremely gravelly	0.15

Note: The suitability scores of 0.84 and 0.7 were based upon research by Ercoli *et al.* (2006), who found that wheat yields were reduced by 16% at a gravel content of 10%, and by 28% with 20% gravels and 34% reduction with 30% gravels. Suitability scores at higher gravel percentages were guesses.

Table D: Effect of gravel size on the crop suitability co-efficient (k).

Predominant gravel size (mm)	Size class	k
2-6	fine	1.0
6-20	medium	0.9
20-60	coarse	0.5
60-200	very coarse	0.2
>200	bouldery	0.1

Table E: Effect of slope on the crop suitability co-efficient (k).

Slope (°)	k	Reasoning	**Reference**
0-7	1.00	The full range of mechanical procedures may be conducted on these slopes	(Webb and Wilson, 1995)
7-11	0.93	11 degrees is considered to be the upper limit to prevent excessive losses from combine harvesters	(Spoor and Muckle, 1974)
11-15	0.75	The upper limit to safe harvesting is considered to be 15 degrees	(Hunter, 1992)
>15	0.00	Unsafe for machinery	

Table F: Effect of soil drainage on the crop suitability co-efficient (k).

Drainage Category	k for sorghum	k for JA
Well drained	1.00	1.00
Moderately well	1.00	1.00
Imperfect	0.98	0.97
Poor	0.95	0.92
Very poor	0.80	0.75

Note: Water-logging for 3 days during vegetative growth of sorghum reduced vegetative yield by 79% (Orchard and Jessop 1984). This same research paper showed that sunflower was more tolerant than sorghum to waterlogging. However JA has tubers and so is likely to be more affected by waterlogging than sunflower which has roots, particularly if the tubers are needed to survive over winter to produce a crop in subsequent years. Therefore a lower suitability score was given to JA than sorghum in wetter soils. Water-logging for 3 days is unlikely in summer in New Zealand, so because both crops are grown in the summer a yield reduction of 0.8 was only assigned to the very poorly drained soils.

Table G: Effect growing degree days (GDD) on the crop suitability co-efficient (k).

Consecutive GDD for sorghum (T_{base} = 11°)	k for sorghum	Consecutive GDD for J.Artichoke (T_{base} = 0°)	k for J.Artichoke
975	1.21	>2455	1.00
900	1.11	2355	0.92
825	1.00	2255	0.83
750	0.90	2155	0.75
675	0.79	2085	0.69
600	0.68	1985	0.61

Note: These suitability scores (Table G) were generated by APSIM by shortening the growing season and investigating the effect on yield. Growing degree days (GDD) were calculated using the formula $GDD = [(T_{max} + T_{min})/2]-T_{base}$. For sorghum a base temperature of 11°C was used (APSIM), and for JA the base temperature used was 0°C (Kays and Nottingham,2005; p 328). For Jerusalem artichoke the data was obtained from a University of Canterbury trial in Hawke's Bay, which had yields from multiple planting and harvest dates (unfortunately there were no data from other locations within New Zealand).

For sorghum the effect of GDD on biomass yield was estimated using APSIM to generate biomass data for Hawkes Bay for 21 years, plotting the biomass yield against GDD and then using multiple regression to find the relationship between GDD and biomass yield (R^2 of 0.87).

Table H: Effect of effective water stress (EWS) on the crop suitability co-efficient (k).

EWS (mm)	k for sorghum	k for JA
0	1.00	1.00
1-20	0.98	0.96
21-40	0.93	0.88
41-60	0.88	0.80
61-80	0.83	0.72
81-100	0.78	0.64
101-120	0.73	0.56
121-140	0.68	0.48
141-160	0.63	0.40
161-180	0.58	0.32
181-200	0.53	0.24
201-220	0.48	0.16
221-240	0.43	0.08
241-260	0.38	0.00

Note: The EWS) that the crop would be subjected to was estimated based on the LENZ annual water deficit for that location (from the LENZ database; Landcare Research, 2012) minus the amount of plant-available water stored in the soil (from the FSL database, Landcare Research 2012). The effect of this degree of water stress on crop biomass yield was then estimated using APSIM. Rainfall was added to the weather files to until maximum yield was reached, and then January rainfall was decreased in increments of 20mm to determine the effect on yield (i.e. crop suitability coefficient, k). APSIM indicated an average decrease in yield for every 20mm of water stress of 5% for sorghum and 8% for sunflower.

Table I: Effect of salinity on the crop suitability co-efficient (k).

Salinity min (%)	Salinity Max (%)	k for sorghum	k for JA
0.00	0.04	1.00	1.00
0.05	0.14	1.00	1.00
0.15	0.29	0.80	0.95
0.30	0.69	0.34	0.80
0.70	1.00	0.08	0.50

Note: The effect of salinity on k for sorghum was based on data from Daniels (2001). For JA, k was interpolated from the data of Huang *et al*. (2010), assuming that k=1.0 for the treatment grown at a salt content of 0.16%. This data did not include treatments with a salinity of 1% so k was extrapolated based on a quadratic equation fit to the data to give k for the 0.7 – 1.0 % salinity categories.

Table J: Effect of soil pH the crop suitability co-efficient (k).

pH min	pH max	k for sorghum	k for JA
7.6	8.3	0.80	1.00
6.5	7.5	1.00	1.00
5.8	6.4	1.00	1.00
5.5	5.7	1.00	1.00
4.9	5.4	0.85	1.00
4.5	4.8	0.65	0.99

Note: The effect of soil pH on sorghum growth was interpolated from data from Duncan (1991). This may have over-estimated the effect of soil pH, as the APSIM model predicts a smaller yield decrease of 9.1% at pH 4.6. The scientific literature suggests that JA has a wide optimum pH range, from 4.5 – 8.6 (Kays and Nottingham 2008). The APSIM model predicted a yield decrease of only 1% at pH 4.65.

Appendix 4: APSIM parameters.

A: Parameters used to run the APSIM simulations to estimate crop yields in different environments.

	Lucerne	Sorghum	Wheat
Cultivar	Kaituna	Late	Rongotea
Sowing density (plants m^{-2})	850	127	250
Sowing date	10 Apr	15 Nov	7 Apr
Harvesting date(s)*	20 Feb, 15 May, 15 Nov, 31 Dec	1 Apr	8 Nov
Nitrogen (kgN ha^{-1})	0	150	80

* Cut to 40 mm height;

The soil was assumed to be 1.8m deep and contain 275mm of plant-available water (PAW), with the irrigation module set to irrigate the crop when the PAW decreased to half of this value. Water was set to be non-limiting because water-stress would be taken into account by the effective water stress (EWS) layer of the map. The simulations were run using weather data (NIWA, 2012) for 21 years for Hawke's Bay and 27 years for Gisborne (note that there was no complete weather data for Tolaga Bay, so the average maximum potential yield for Tolaga Bay was assumed to be the same as that for Gisborne).

The growing period was assumed to be the same as that used for the 2009-10 field trial (from the 17th of November to the 21st of March) for all years and at both sites.

B: Changes to the APSIM model

Changes to the APSIM model to better estimate the high biomass yields observed in cooler climates

Note that a number of changes were made to the sorghum model to better match the high yields were observed in field trials. These were:

(1) Increase radiation use efficiency from 1.25 to 1.6. The value of 1.25 in the sorghum model was replaced with the same values as used in the maize model (i.e. for stages 1 – 12 the values used were 0, 0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.4, 1.3, 1.3, 0, 0). This change had the greatest effect on increasing yield.
(2) The light intensity at which the leaves were dying was decreased from 2 MJ m^{-2} to 0.5 MJ m^{-2}. This gave a much more realistic leaf area index because the predicted rate of leaf death with a value of 2 MJ m^{-2} was much faster than the rate observed in the field trials.
(3) A small change in the rate at which thermal time was accumulated was also made, to increase the rate of leaf appearance slightly at lower temperatures. The rate at which thermal time accumulated was changed from 0, 19, 0 at cardinal temperatures of 11, 30 and 42 °C respectively, to 0, 1, 19, 0 at cardinal temperatures of 10, 11, 30 and 42 °C respectively. A similar, although larger, change was found to be necessary when adapting a maize model (developed with Australian and USA data) to New Zealand conditions (Wilson *et al.*, 1995).
(4) x_ave_temp was changed from 8 20 35 50 to 8 14 35 50. This change increased yields in the Hastings run by 5 t DM ha^{-1}.

Appendix 5: Summary of the crops included in the screening trial for biogas production (Year 1)

The 'pros' and 'cons' of their use for the closed loop N system, based on literature. Lucerne and Miscanthus are not in the trial plots (see Results and Discussion)

Name	Pros	Cons
Maize (*Zea mays* late maturing hybrids)	High yields (20 to 35 tDM ha^{-1}) Good digestibility Established production systems No aging or quality issues if harvest is delayed High DM% in harvested – good for long distance carts Chemical weed control well established Can be planted at least 4 weeks earlier than sorghum	Usually planted with intensive ground preparation (but minimum tillage should work as well) Relatively high fertiliser inputs required Less drought tolerant than sorghum and millet
Sorghum (*Sorghum bicolor*) (*S.sudanese*) + hybrids	Lower nutrient requirements than maize drought tolerant once established (>40 cm high) One and multi cut management Can be planted after late maturing winter crops Herbicide weed control possible Yields of 18 – 23 t DM ha^{-1} after *c.*135 days in Germany biogas quality better than maize Drought tolerant	Only for warm regions of NZ Cannot be planted before November Variable yields Potentially lower digestibility Low DM in harvested biomass (using the maize harvest system), requires wilting Relatively high nutrient requirements to achieve decent yield.
Pearl millet (*Pennisetum glaucum*)	Very drought tolerant Can be planted after late maturing winter crops Lower N requirements than maize	Only for warm regions of NZ Cannot be planted before November Lower yields than sorghum
Forage sunflower (*Helianthus* *annuus*)	Can be planted early in spring (young plants can withstand -5°C) Relatively drought tolerant Relatively low nutrient requirements Early harvest allows early establishment of follow-up crop Ideal for lighter soils Chemical weed control possible - One cut management	Relatively low yield (7 – 10 tDM ha^{-1} in the UK) Fluffy biomass difficult to ensile, particularly when too dry Little experience in growing the crop in NZ Low DM% Requires relatively warm climate (>14°C average temp.)
Jerusalem artichoke (*Helianthus tuberosus*)	Established crop survives frost Easy to establish from very small root fragments. Low fertiliser requirements to establish, may increase in later years No chemical weed control required Establish topinambur once and harvest for 5 to 10	Parts of proposed production system untested Bio-security issues, may become a weed Below-ground biomass produced not easily utilised for biogas production The lignin fraction of the foliage increases rapidly towards winter.

subsequent years

Forage yield potential (6 – 20 tDM ha^{-1}).

One cut yr^{-1}

Maize silage technology for harvest

Appendix 6: Maps showing suitability of marginal land to grow sorghum or JA.

Figure A: Map of Heretaunga plains and surrounds showing the suitability of land for Jerusalem artichoke. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for JA of 1 is estimated to yield 15.6 tDM ha^{-1} in an average year. Land with k=0.97 is assumed to yield 0.97 × 15.6 = 15.1 tDM ha^{-1} in an average year.

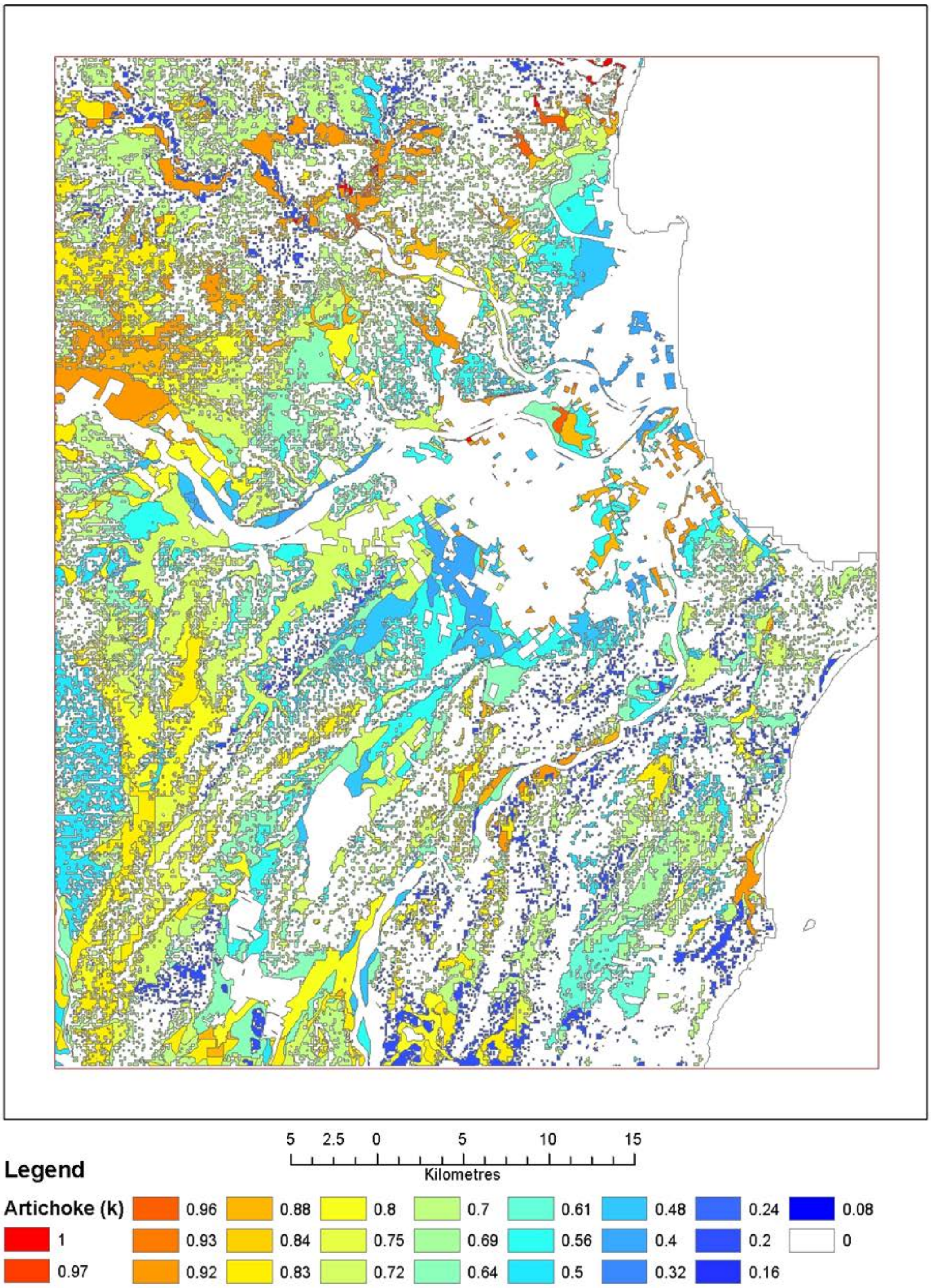


Figure B: Map of Patutahi near Gisborne showing the suitability of land for sorghum. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for sorghum of 1 is estimated to yield 27.3 tDM ha^{-1} in an average year. Land with k=0.98 is assumed to yield 0.98 × 27.3 = 26.8 tDM ha^{-1} in an average year.

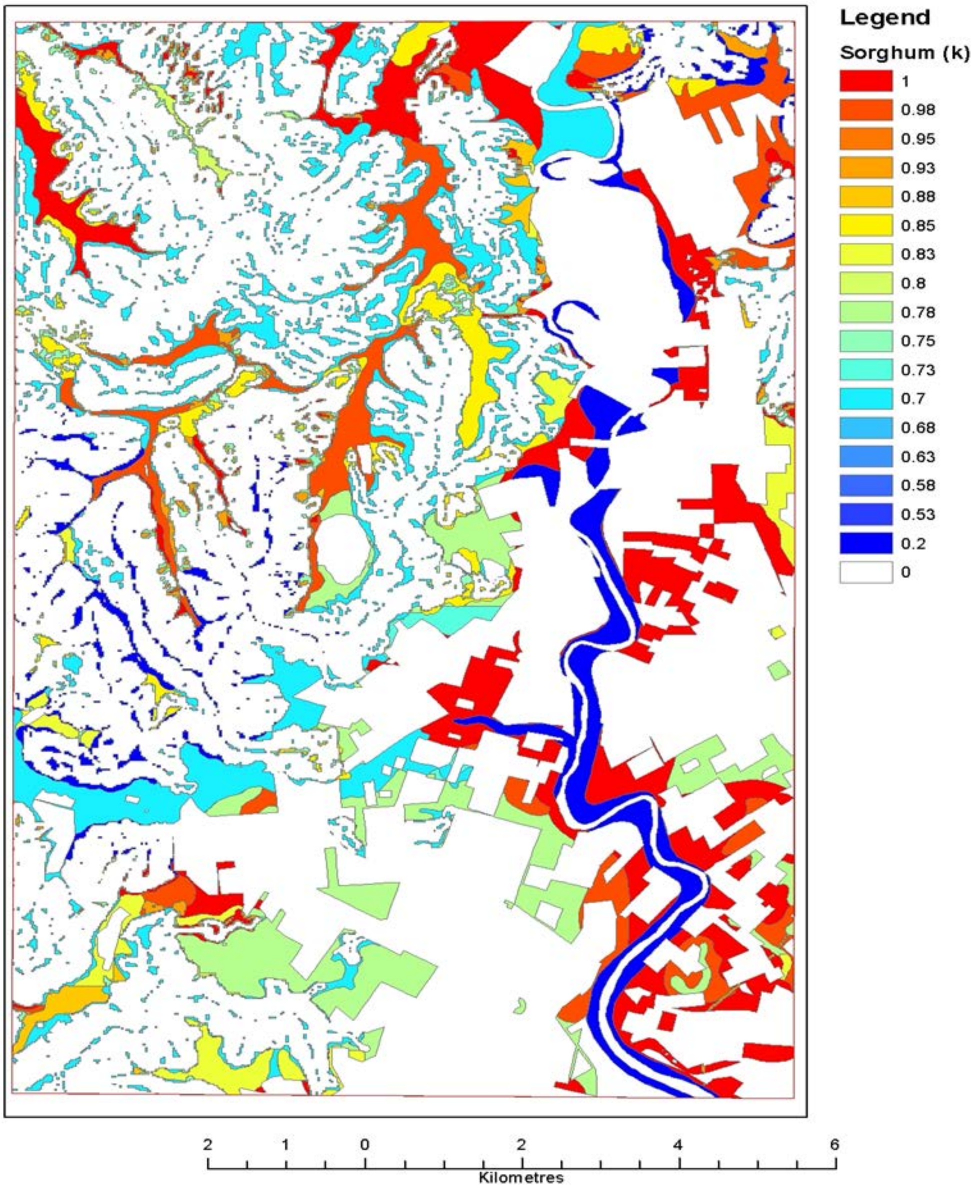


Figure C: Map of Patutahi near Gisborne showing the suitability of land for Jerusalem artichoke. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for JA of 1 is estimated to yield 16.2 tDM ha^{-1} in an average year. Land with k=0.98 is assumed to yield 0.97 × 16.2 = 15.7 tDM ha^{-1} in an average year.

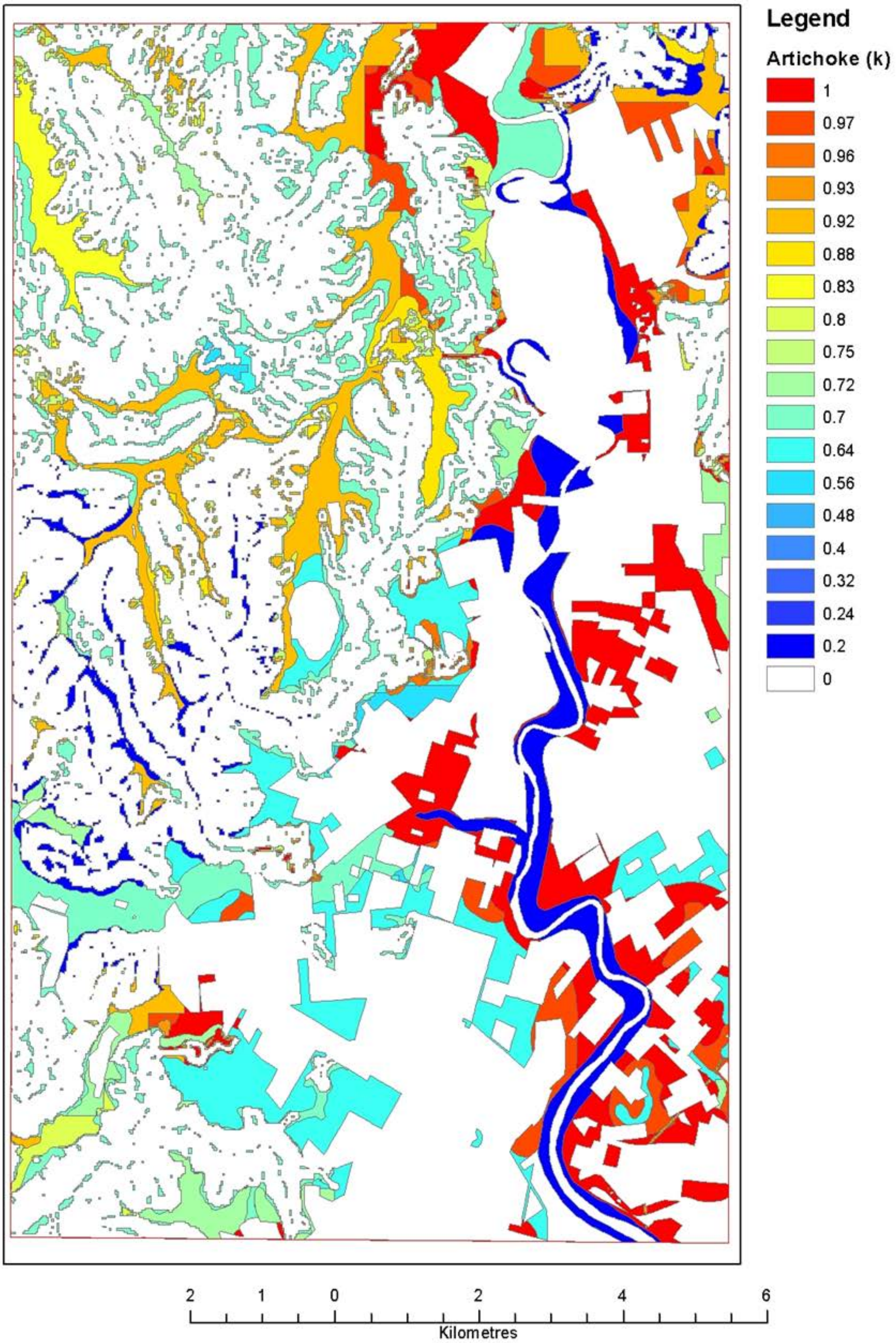


Figure D: Map of Tolaga Bay showing the suitability of land for sorghum. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for sorghum of 1 is estimated to yield 27.3 tDM ha^{-1} in an average year. Land with k=0.98 is assumed to yield 0.98 × 27.3 = 26.8 tDM ha^{-1} in an average year.

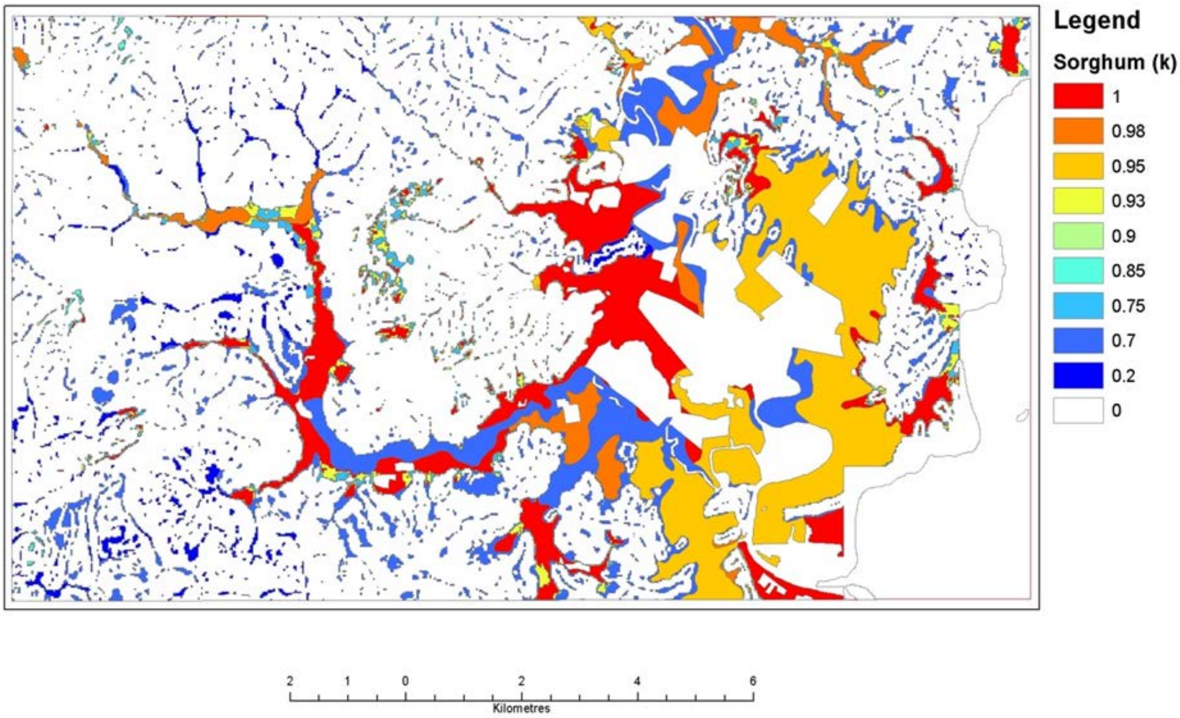
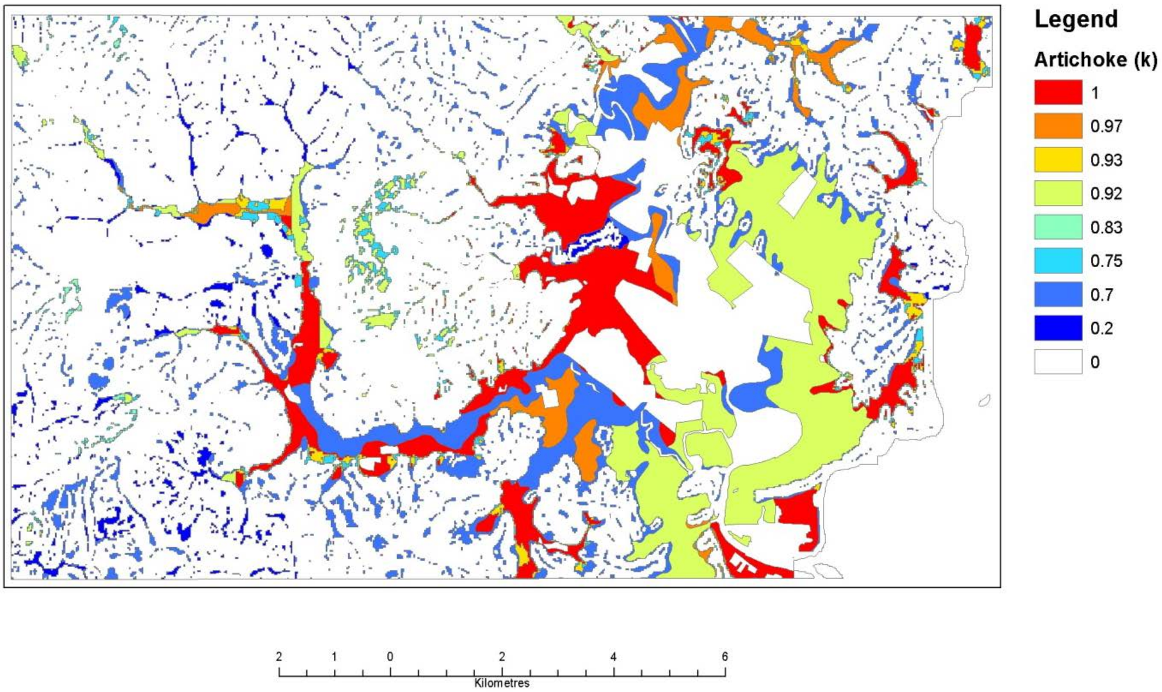


Figure E: Map of Tolaga Bay showing the suitability of land for Jerusalem artichoke. Land that is too steep or not marginal is coloured white. Land with a suitability co-efficient (k value) for JA of 1 is estimated to yield 16.2 tDM ha^{-1} in an average year. Land with k=0.98 is assumed to yield 0.97 × 16.2 = 15.7 tDM ha^{-1} in an average year.



Appendix 7: Workshop Taupo

Program with topics/speakers

RURAL BIOFUELS – A NEW LAND-USE OPPORTUNITY FOR A GREENER NEW ZEALAND

Venue: The New Zealand Clean Energy Centre

223 State Highway 5, Taupo

07 376 7107

Date: Tuesday June 19th 2012 **Time:** 11am – 3pm

Programme

11.00-11.05 Welcome and introduction (Zac O'Brien)

11.05 – 11.40 Future fuels for rural New Zealand (Dr. Rocky Renquist and Stephan Heubeck)

This talk outlines the need for biofuels in New Zealand, and specifically biomethane. It examines what crops would be suitable for biomass production in the North Island.

11.40 – 11.55 How do I make biogas on the farm? (Stephan Heubeck)

This talk explains how a farmer would make biogas and examines systems that are already working in Europe.

11.55 – 12.30 Closed Loop Nitrogen cropping for biogas energy. (Dr Huub Kerckhoffs)

This talk describes the Closed Loop Nitrogen cropping system and gives field trial results.

12.30 – 1.10 Lunch

1.10 – 1.35 Miscanthus: A promising new biomass crop for New Zealand (Peter Brown)

This talk outlines the exciting commercial possibilities for both growers and biomass users with this versatile new low-input, high return crop.

1.35 -1.55 Expected crop yields and N use (Dr Stephen Trolove)

This talk takes the field trial data to a regional scale and also discusses suggested yields and N use for Taupo.

1.55 – 2.30 Can I make money from growing energy crops? Two possible scenarios (Stephan Heubeck)

This talk discusses gross margins for growing crops for biogas production.

2.30 – 3.00 Discussion

This includes input from Chris Timmerman from Bio-Energy solutions who builds biogas plants for dairy farms. Please note that people are welcome to stay longer if they wish to have more detailed discussion.

Appendix 8: FAQs

In this appendix, we answer some frequently-asked-questions (FAQs) raised at the organised workshops and other interactions with stakeholders and interested parties. They are dealing with perceived risks and feasibility around the possible application of biogas in the NZ. Answers are formulated in a wider context but are referring and linked to the research project where appropriate.

(1) Why is there little use of natural gas in NZ even at a 'low' cost of $10/GJ?

Natural gas (NG) cost only 10$/GJ (excluding lines and capacity charges) if one can fuel several hundred vehicles from a single refuelling point. At commercial rates NG is still cheaper than diesel / petrol, but the difference won't be as large as indicated by comparing the wholesale price of NG to the retail price of diesel. Many businesses lease rather than own vehicles or use subcontractors (so behaviour is not pure rational economics based on price). In addition, some ideally suited fleets have a high turnover (i.e. ~3yrs) too short for payback, and recouping value from a used vehicle is difficult. A complicating factor in NZ is that the gas grid coverage is relatively sparse in NZ and does not existent in the South Island. Factors like the (non)-availability of spare parts for a new gas-fuelled fleet is a deterrent for entry at very small scale. Overall the lack of profile (i.e. policy support) and stringent opposition from existing fuel (oil) industry is not favouring the use of alternatives.

(2) What gas price is required for biogas to work in NZ?

"The natural gas price is rather 'irrelevant' for a CLN biogas frame-work to work". It is more important to ask what the alternative costs for the several energy components for which biogas can be used are i.e. transport, electricity and heat. Biogas applications which are making optimal use of these three components simultaneously are very likely to be economically viable in the NZ context as well. However, the economic assessment (see 3.11) of the CLN biogas system will give the reader a basic understanding of the issues. See also question 18.

(3) What are the chances seeing gas vehicles replacing diesel ones in NZ rural areas?

There is the classical risk of a chicken and egg problem, hence the organisation along the lines of a farmers group / co-operative to ensure the buyers of gas vehicles have a secure supply of fuel amongst themselves. The main trigger would be when diesel vehicles/farm equipment is replaced by new imported gas vehicles, but retrofits for certain vehicles are possible and sensible as well. Initially there can also be a benefit with retrofits of petrol utility vehicles and farm trucks. Potential external users (i.e. rural freight companies) need to be integrated with the group early on if partnership is to be successful.

(4) What is the cost of a CNG vehicle?

This varies very widely. A retrofit kit for a 260 HP truck ranges between $10,000 and $20,000 (2012). Contrary to this, OEM truck manufacturer in Europe and North America have announced that the only difference between a new diesel and gas-diesel truck will be the cost of the gas tanks. This could be more than a marketing gimmick, since especially with Euro 5 and 6 emission rules, the extra cost of gas equipment on the truck, could be compensated for by the reduced need for exhaust gas cleaning (since gas burns much cleaner than diesel).

(5) Are re-fuelling stations (too) costly?

Farm and municipal AD plants in EU commonly have refuelling stations and the costs are within the single digit % of the overall AD plant set-up. Furthermore this report is not proposing nation-wide infrastructure for all transport.

(6) What are the costs of gas upgrading and compressing?

Energy-wise it is 4-5% parasitic energy for upgrading, and 5-10% parasitic energy for compression, however in a rural set-up the "loss" (waste heat from the compressor) would be re-used for digester heating, which has to be deducted from the overall parasitic energy budget. The 30% parasitic energy consumption value we used for the CLN system calculation (see 3.xx) may therefore represent a conservative upper limit.

(7) Are large, centralized structures the best way to supply green fuel in NZ?

There is no 'one-size-fits-all', and one of the objectives of CLN was to show a different alternative. Furthermore, the idea that NZ fuel needs can be met with 3 or 4 large plants does not recognise that is not the way green energy has successfully developed overseas. Rural development benefits of renewable energy projects have been successful in Germany where the installations are owned by many rural communities; in Denmark where the installations are primarily owned by citizens groups; in Sweden where the local councils play a big role, and in Brazil where the government is actively engaging with bigger structures (which are larger than in Europe). However, there are renewable energy projects where disadvantages outweigh the benefits, like in the US and Southeast Asia, where the ethanol mills and palm plantations respectively are in the hands of a few private investors, who have little regard for aspects like rural development, or potential secondary environmental benefits of green energy projects.

(8) Should natural gas use be encouraged in transport as a transition to compressed biogas in NZ?

It could assist getting infrastructure in place, however replacing current petroleum use with natural gas (NG) means substituting one finite fossil resource with another finite fossil resource. Still, it is better to use NG for transport (to improve the NZ balance of trade) rather than other NG uses that could be replaced by renewable electricity.

(9) What rural energy demands could be met with biogas?

Agricultural vehicles would use <8PJ if it is diesel they displace (13PJ diesel for farm, forest and fish sectors). Rural petrol use is <5PJ. Other rural uses may include drying and heating in areas away from the NG grid, and co-gen in areas with poor electricity supply.

(10) Can farmers supply the biomass economically?

The overall fuel production and grower profits both depend on achieving expected yields, but the answer is definitely 'yes, it is possible'. The calculations in section 3.10 are very conservative for the new species JA, starting with the low DM estimated using the APSIM sunflower model. Field trial JA yields are very much higher and JA is not affected by pests and diseases that were also used to discount sunflower yields. We also assumed a further 10% loss of biomass in the process of transportation, silage making and loading into the digester and reduced the DM tonnage by another 11% to calculate volatile solids (the portion of DM that biogas is produced from). For overall production we also based it on the use of only 5%

of the marginal land in each region, so a shortfall from expectations could be easily made up for with extra planted area. Grower profit potential is based on low production costs compared to maize and making a better use of lower value land; biomass prices used to assess AD plant economics average $140/tDM. Gross return per ha would be low ($1750/ha) if the yield of JA was that used in the model estimate, but fairly good ($3500/ha) if JA can yield 25tDM/ha (suggested by research plot yields >35 tDM/ha).

(11) Will methane leaks in AD systems compromise GHG footprint reduction?

Methane is a strong GHG, but digester design and covered storage of digestate are now proven control measures to keep losses very low. Studies in Europe have shown that the majority of methane losses from a group of biogas plants are mostly caused by a small number of badly performing plants, rather than a more or less even baseline for all biogas plants. Proper operation of biogas installations is therefore important, and technically not difficult, for keeping methane losses low. Furthermore biomethane as a fuel would give greater GHG reductions compared to other alternative biofuels.

(12) A *virtual* CLN assessment does not provide a 'proof of concept'!

The 'virtual' system assessment was the research approach and the only option for a 3-year project, but in hind-sight a different word than 'proof' would be better. As noted earlier there are EU research results and ample commercial results to show that each component of biomass cropping with AD digestion and use of digestate does work overseas. Our component tests in NZ provided the inputs for a NZ assessment and we fairly concluded that no limitation to successful introducing the described CLN cropping system in NZ was identified.

(13) This CLN cropping system for biogas production will not get started due to the need for both AD plant investors and biomass growers to have the other party in place first?

Solutions are available for the 'chicken or egg' dilemma. As a base case it is envisaged that a group of farmers can build an AD plant and supply it. Furthermore AD plants initially processing waste materials could expand in a step by step transition to use more and more CLN biomass.

(14) Biomethane is not a 'perfect substitute' for diesel

Taken into account the aspects about gas vehicles and NG price discussed above, diesel is a non-renewable fossil fuel that will need to be replaced regardless of whether a 'perfect' alternative is found (taking a longer time scale than some economists allow) and should be replaced ASAP to protect biosphere health. The best substitute need not to look like diesel, it just needs to offer the best solution using NZ resources to fuel first generation engines during the decade(s) before they are replaced by more appropriate (future) technology.

(15) The logistics for use of digestate may not be cost effective (e.g., transport distances)

This is not a barrier in the EU. Small biogas plant unit sizes help to keep digestate and biogas feedstock logistics cost and effort to a minimum. For larger set-ups solutions that increase cost effectiveness of logistics include separating liquid and solid fractions, which helps to increase economical transport distances for a part of the digestate nutrients.

(16) Does only using low-cost waste streams make sense for AD biofuel?

The total energy production from all waste streams is about equal to that of agricultural diesel use, but wastewater treatment plants and food processor locations are only within range of a tiny fraction of the proposed marginal farm land. Just 5% of this land should produce 3 times farm diesel use, allowing for other rural uses of the biogas. As petroleum prices increase, the use of cropped biomass to substitute these non-renewable energy supplies will become more attractive in an increasing number of situations and locations.

(17) Are liquid fuels from wood a better option?

This is not an either or case. The described CLN biogas fuel can complement a wood fuel future by playing out its specific strengths: (1) Short lag time to grow biomass; (2) Modest scale and modest capital requirements massively increases the pool of potential players; (3) Technology is proven and works here and now – no need for future research to find enzymes and catalysts; (4) Logistics advantage due to localised scale; (5) Feed-stock flexibility reduces risk for finding / growing appropriate feedstock in the future. (6) Higher net energy yields per ha with CLN in many appropriate locations.

(18) How is the value of biomethane best compared to the natural gas price (and which natural gas price)?

Setting the value equal to the current pipeline price of NG is not helpful. Comments in the introduction section (see Table 1) make this clear that the appropriate scale is much smaller than wholesale scale (and the associated NG price at smaller scale is much higher).

Appendix 9: 'Energy Supply Margarethen' case study

The following article describes the biogas plant in Margarethen am Moos (Austria).

(Source: http://www.nachhaltigwirtschaften.at/(en)/publikationen/forschungsforum/091/teil2.html)

The biogas plant in Margarethen am Moos (Austria)

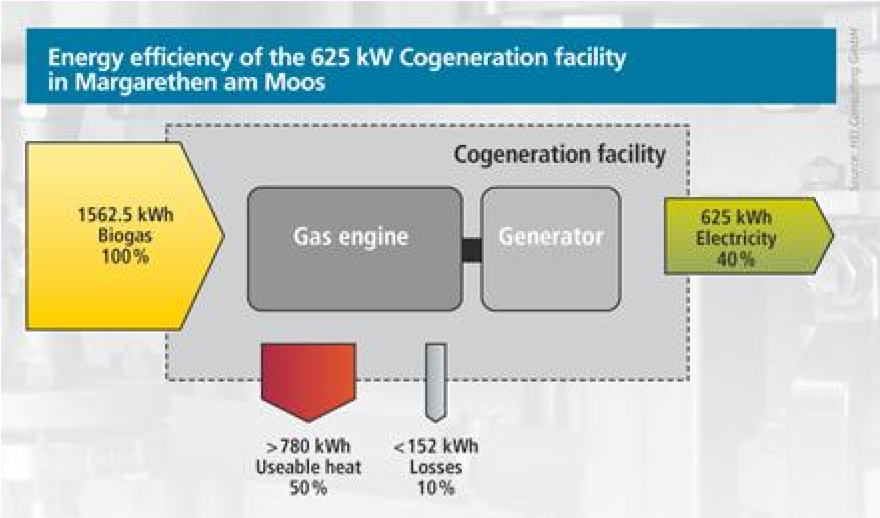
Generating heat, power and transport fuel

The biogas facility in Margarethen am Moos is operated by a cooperative called EVM ("Energy Supply Margarethen") and made up of 12 farmers who own and operate the advanced bioenergy facility. In 2004 the cooperative took the decision to set up a 500 kW_{el} biogas plant to generate electricity and heat for running a district heating network for 120 households.

To supply this facility renewable raw material is grown on an area of roughly 200 ha around the plant. Since precipitation in the region in question is limited (600 mm per year), plants that cope well with dry conditions are used, mainly sorghum and sudan grass; the cover crop in winter is rye. Lucerne, grass and clover can also be used. High energy yields can be achieved if the substrate for fermentation is chosen intelligently and state-of-the-art fermentation technology is employed.

In the course of the last few years the facility was fine-tuned and enlarged. To make it more energy-efficient, the exhaust gas losses were reduced and power-generating capacity increased to 625 kW_{el}; this was simply a matter of modifying the Jenbacher 316 engine. In a standard cogeneration facility around 20% of the energy content supplied is lost, owing to the exhaust-gas temperature (roughly 200 °C) and radiant heat lost from the engine. Here these losses were cut to 10 %, by designing the exhaust gas heat exchanger for 100 °C and lowering the stack temperature to 100 °C. To cope with peaks in demand and as a standby in emergencies, a 900 kW boiler is on hand; with a dual-fuel burner, it can run on biogas or biodiesel. This combination of cogeneration facility and boiler can deliver up to 1.6 MW of heat, thus ensuring adequate heating even at extremely low outdoor temperatures.

To increase the value to the local community further, some of the biogas is purified to engine fuel standard and sold on the spot, rather than being fed into a grid; this started in 2007. With the right technology biogas can be processed to match natural gas for purity, and then used to fuel motor vehicles; in contrast to generating electricity from biogas, this processing involves not energetic conversion but an increase in energy density – incombustible CO_2 is separated from energy-rich CH_4. The purified biogas contains up to 98 % CH_4.



Source: HEI Consulting GmbH

In Austria a statutory order defines the quality standard applying to gaseous transport fuels. The main considerations are the methane content and the relative density. The biogas facility produces around 25 kg/h of purified biogas, equivalent to roughly 35 l/h of petrol. Sold under the brand name "methaPUR", it contains more than 95 % methane and complies with international standards for gaseous engine fuels as regards calorific value, Wobbe index and density.

After purification, a high-pressure compressor compresses the biogas to 300 bar and stores it in a high-pressure storage vessel – part of the biogas filling station that started operation in December 2007. The fuel facility functions on the supply-on-demand principle, utilizing the high-pressure storage vessel as a buffer element. The filling station is not open to the general public; customers are required to register with the cooperative first. They then receive a key tag with a built-in chip to activate the filling system. The filling station is self-service; the customer pays by debit card or credit card. "methaPUR" costs no more than the natural gas sold at public filling stations.

Biogas refuelling station (located at the Margareten am Moos biogas facility).

(Photo by S. Heubeck).

In the business case for the facility in Margarethen am Moos a payback period of 6 years is planned for the investment in fuel production. By then 200 cars with an average fuel consumption of 5 kg gas per 100 km, travelling 15 000 km per year on average, should be using the filling station regularly. The business case is based on a price of 90 Euro per t of substrate for the biogas facility.

Producing and using biogenic CNG as an engine fuel has various positive aspects:

- Biogenic CNG is produced locally from renewable resources.
- The entire chain of value creation – making and processing biogas, selling the fuel and using it– is located in the region in question (substrate suppliers, facility operator, fuel consumers ...).
- Production and sale are not dependent on a gas grid, so biogenic CNG can in principle be produced in any biogas facility, regardless of location.
- The fuel is largely climate neutral; in use it releases scarcely any pollutants, such as incompletely combusted hydrocarbons or particulates.
- Producing biogenic CNG can be economically attractive as a supplement/alternative to generating electricity from biogas.

The purchase price of a car running on natural gas is currently close to that of a comparable diesel-engine car and around 20 % above the price of a comparable petrol-engine car. At the moment there are somewhat more than 3000 cars running on natural gas in Austria, with around 140 filling stations selling natural gas. From 2008 on the approach successfully pioneered in Margarethen am Moos should be copied elsewhere; it is planned to implement 20 to 25 more biogas filling stations along these lines.

Tractor fuelled by biogas as used at the Margarethen am Moos facility; fuel tanks are located at the top of the cabin as shown in right picture.

(Photo by S. Heubeck)

Factbox: Biogas facility in Margarethen am Moos

Nawaro biogas facility, generating capacity 625 kW

- 2 digesters (2200 m^3 each)
- Fermenter temperature 40° C
- Sealed storage vessel (4500 m^3) plus open storage tank (5500 m^3)
- Final residue is separated off so that water can be returned to process
- Residue cake is sold to some extent
- Heat is supplied via a district heating grid 3.5 km long
- Heat users: residential area, farms, stately home, council kindergarten
- Connected load (heat): 1.2 MW
- Fuel production: 25 kg/h biogenic CNG