Closed-loop N cropping system: new land uses to make rural biofuel

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Abstract

A Closed-Loop Nitrogen (CLN) bioenergy cropping system could provide rural New Zealand with a substantial supply of biomethane, a sustainable biofuel. Crops are anaerobically digested and nutrients returned to the biomass paddocks, thereby closing the loop. Biomass species were selected that proved well-adapted to grow on marginal land, such as ‘summer dry’ land, rather than the best arable food crop land, and that also achieved good yields with low agronomic inputs. The low-input perennial Jerusalem artichoke could produce biomethane yields per ha of up to 5,000 m^3 and drought-tolerant forage sorghum could produce up to 8,000 m^3 CH4/ha based on test plot DM yields. A scenario analysis with 12 farmers growing 220 ha of biogas crops for a medium-sized digester near Lake Taupo indicated the potential to produce a net supply of biomethane energy equivalent to 904,000 litres of diesel per year. The cost of production of biomethane was very dependent on feedstock crop prices, and confirmed that successful biogas ventures must be tailored to individual situations. A model applying field trial results to New Zealand-wide scale indicated that if CLN biomass crops were grown on only 5% of ‘summer dry’ arable land they could supply 19.7 PJ per year of fuel energy, more than twice the current annual diesel fuel needs of New Zealand agriculture. To digest the biomass grown on 5% of summer dry land would require only 570 biogas plants of the size of the Lake Taupo scenario described in this paper. The CLN cropping system has the potential to offer many benefits to rural communities and is also one of the most sensible approaches to mitigate agricultural greenhouse gas emissions.

Additional keywords: Anaerobic digestion, methane, biomethane, biogas, sustainable production, renewable energy, rural development, *Helianthus tuberosus, Sorghum bicolor, Vicia faba, Trifolium incarnatum*

Introduction

Dual challenges for New Zealand agriculture: climate change and uncertain fossil fuel supplies

Challenges to the New Zealand rural sector in coming decades include the impact of climate change. This may demand significant land use change. In areas that already have sub-optimal conditions like summer moisture deficit farmers are eager to explore adaptation options, particularly as the deficit is predicted to get worse in northern and eastern areas (MfE, 2008). Land use changes and 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 greenhouse gas (GHG) emissions, agri-chemical use, and nutrient leaching.

Over the same timeframe, energy supply security to the rural sector will become more problematic. New Zealand's Energy Outlook (NZ Energy Outlook, 2011) projects oil prices to remain (on average) elevated at US$ 130/barrel until 2030 in their reference scenario, but their high oil price scenario has 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/gigajoule (GJ) in real energy terms. However, influential analyst Kjell Aleklett, President of ASPO International (Aleklett, 2012) considers that due to stagnating world oil production, potential political tensions in key producing countries and rapidly rising petroleum demand in Asia, oil prices will starkly increase and create difficulties for adequate and timely supply of petroleum in both developing and OECD countries. This recent view is consistent with IEA chief economist Fatih Birol, who already stated in 2009 that "the output of conventional oil will peak in 2020 if oil demand grows on a business-as-usual basis" (The Economist, 2009). A significant concern for New Zealand in this context would be the increasing current account deficit if the price of oil imports rises faster than the price of agricultural exports.

The general economic picture also has many in the rural sector looking to minimise business risk and diversify core primary production away from established products and markets into new areas.

Rural energy solutions

New Zealand has a large proportion of agricultural GHG emissions in its overall GHG footprint, so a focus on the reduction of the agricultural component is important. With current technologies it is easier to make large reductions in the fossil fuel component of these emissions than to reduce emissions of methane (CH_4) from ruminants (Murphy *et al.*, 2009). The rural sector could utilise some of the New Zealand land base for purpose-grown bioenergy crops, which will reduce the need for fossil fuels. This potential has recently been quantified in a bioenergy industry report (BANZ, 2011). This will also create a more secure rural fuel supply, diversify land use and reduce agriculture's environmental footprint. The 'ideal rural energy solution' would have to fulfil a large range of often mutually exclusive conditions, including production of a fuel that has a high energy content, is flexible in its use and produced from crops that:

(a) have very high biofuel yields per hectare on marginal lands;
(b) use minimal inputs;
(c) have a low environmental impact; and

(d) are largely compatible (including in terms of scale) with existing infrastructure and processes.

No energy system can satisfy all of these demands simultaneously, so certain compromises will be necessary.

A longer term approach is to convert marginal (often steeper) agricultural land to energy forestry (or combined energy, biomaterials and timber forestry), as identified in the Bioenergy Options for New Zealand project led by Scion (Hall and Jack, 2009). Their scenarios showed a huge environmental benefit as well as economic indicators that make this approach worth considering. Limitations are mainly in relation to scale, large capital requirements (including overseas investments) and compatibility issues with existing farming operations. Furthermore, some technological aspects (like enzymes, gasifier technology, catalysts) of the conversion of wood into usable energy products are not yet clarified, and it is unlikely that most wood conversion processes can ever be downscaled for application at farm level or in a smaller New Zealand regional context.

The agricultural sector should prepare for an uncertain energy future, and consider other bioenergy crops and processing pathways as smaller scale alternatives to trees, that can provide a farmer group or rural community with their annual energy requirements of between 1,000 to 100,000 GJ/yr range (equivalent to 28,000-2,800,000 l diesel fuel/year (NZ Energy Data File, 2011)).

Technology schemes that successfully supply this scale of biofuel include biodiesel from oilseed crops and bioethanol from grain fermentation. However, both technologies suffer from low net energy yields per hectare of crop (generally <2,000 l diesel fuel equivalent/year), high energy consumption by the conversion technology itself (i.e. distillation) and very little flexibility regarding soil and climate conditions, since each technology is generally tailored to specific oilseed or sugar/starch crops.

The third appropriate rural-scale technology alternative for addressing the challenges outlined above is the production of biogas (CH_4) via anaerobic digestion of bioenergy crops, which is the technology of choice described here.

Biogas production via anaerobic digestion

The bioenergy cropping system presented in this paper has biogas production as a central feature. Biogas production from bioenergy crops does not fundamentally differ from the anaerobic digestion of animal manure and farm wastes or municipal wastewater treatment sludge and these three sources can often be combined. anaerobic digestion of energy crops is generally conducted in heated and mixed concrete or steel digester tanks, at mesophilic temperatures (35-39°C) (Figure 1). The energy crop feedstock is often ensiled to ensure year-round supply. The feedstock is introduced into the digester tank with the help of an auger or hydraulic ram. Paddle or pump mixers ensure a good mixing of incoming feedstock with the bacteria-rich liquid slurry inside the digester. Feedstock is added daily, and the feedstock retained inside the digester for 30 to 40 days, during which time anaerobic bacteria degrade most non-woody materials to biogas. Biogas feedstock is often measured in kg volatile solids, calculated as DM minus the mineral ash content, which cannot be degraded by microbes. The volatile solid fraction generally ranges from

88% to 96% of the DM. The anaerobic digestion process does not fundamentally alter the nutrient content (N, P, K and trace elements) of the input material, but converts the nutrients into plant available forms (i.e. organic N into ammonium). The original nutrient content is preserved in the digestate, a homogenous slurry that is removed daily from the digester and stored in an adjacent covered pond (for up to 4 months) to be recycled back to agricultural land where the energy crops are grown. This largely closes the nutrient loop, which is a key feature of the CLN system.

Raw biogas produced by the digester is a water-saturated mixture of gases with a CH_4 content of 55-65% and a carbon dioxide (CO_2) content of 35-45%. Raw biogas will also contain varying amounts of corrosive impurities such as hydrogen sulphide (H_2S), ammonia (NH_3) and other volatile organic compounds (VOC's). Without much additional purification, raw biogas can be used as a boiler fuel or for electricity generation. However, the highest-value use for biogas is as vehicle fuel, which requires upgrading of the raw biogas to biomethane by pressurised water scrubbing (Figure 1), pressure swing absorption or chemical washes to remove CO_2, H_2S and other contaminants, yielding a dry and clean bio-methane gas of >97% CH_4 purity. For use in vehicles, the purified biomethane is compressed to 200 bar and stored in standard natural gas pressure cylinders on-board the vehicle (Figure 1). Bio-methane can be used to fuel a range of vehicles such as cars, trucks and tractors since gas conversion options for both spark ignition and diesel engines are available, and are increasingly offered by vehicle manufacturers.

Figure 1: Photos clockwise from the top left: biogas digester at the Margarethen am Moos biogas facility in Austria, scrubbing tower in Auckland and diesel-to-biogas tractor also at the Margarethen am Moos biogas facility.

Digester heating represents internal energy consumption by the process, but feed stocks with high DM% such as energy crops help to minimise heating (and drying) requirements; furthermore, waste heat (i.e. generated from biogas compressing) can be employed for this purpose. Biogas purification and compression as well as crop cultivation and cartage of feedstock to the digester and digestate back to the paddock represent further internal energy consumption. In an early New Zealand study, Stewart (1983) analysed the production of biomethane from purpose-grown biomass crops in New Zealand, finding that the required energy to operate the digester and purify the biogas into compressed biomethane was 25% of the gross energy return, without recycling compressor waste heat. Stewart (1983) also calculated energy inputs to grow the crops as about another 5% (D.J. Stewart pers. comm. 2009). These values fall within the broad range of biogas system internal energy requirements determined by Börjesson *et al.* (2010).

While up to 30% internal energy consumption in a system to produce biogas may appear high, these figures need to be compared with other alternative fuel pathways or the current petroleum provision system. Cleveland (2005) indicates 10% to 17% internal energy consumption for finished petroleum products, while Szklo and Schaeffer (2007) estimate the internal energy consumption of the petroleum refining process alone to be between 7% and 15%. Also, unlike petroleum refining, all the internal energy consumed in a biogas system is provided by renewable resources. Furthermore, while biogas technology will become more efficient as the technology is further developed, the internal energy consumption of fossil fuels will only increase because a larger share of fossil petroleum supply will need to come from deposits (tar sands, heavy oil) that require more energy to produce.

The production of biogas has been evaluated as the most suitable 'rural-scale' energy technology (Murphy *et al.*, 2009) because it enables plant nutrients to be recycled, and is very scalable and adaptable to suit rural conditions. Since anaerobic digestion is capable of processing the whole plant, rather than just part of the plant (e.g. seeds or tubers), and because internal energy consumption is only moderate, the anaerobic digestion process can convert the biomass from a hectare of land into at least three times more fuel energy than produced by one hectare of oilseed crop for biodiesel or grain crops for bioethanol (Börjesson *et al.*, 2010; BANZ, 2011).

Additional environmental benefits of using biogas as a petroleum substitute include very clean vehicle exhaust gases and less engine noise from a biogas powered vehicle.

Objectives of the study

This paper gives an overview of a novel bioenergy cropping system as part of a New Zealand biofuel feasibility study aiming to address the following objectives:

(a) define and identify relevant 'marginal sites' and map their New Zealand area;
(b) test-grow biomass crops for use in CLN (and rates of N required);
(c) test the anaerobic digestion digestate as an N fertiliser;
(d) measure biomethane yield per kg of ensiled biomass, and per ha;
(e) assess biomethane yield potential from a 220 ha crop scenario;
(f) assess the potential for New Zealand biofuel crops to supply rural fuel needs, and
(g) calculate the potential of CLN biofuel cropping to reduce agricultural GHG.

Two aspects are being published separately. One, to be published, will describe the biomass cropping research in greater detail in terms of biomass and biomethane yield per ha. The other, already published (Trolove *et al*., 2013), assessed the potential of anaerobically digested crops to supply New Zealand's rural fuel requirements.

The Closed-Loop Nitrogen cropping system

CLN system description and environmental benefits

The CLN cropping system involves growing crops that produce a large amount of biomass on land that is marginal for food crop production and converting the biomass to energy via anaerobic digestion, as previously described by Renquist *et al.* (2010).

The anaerobic digestion process, as described in the introduction, fully conserves the nutrients in the digestate, which can be returned to the field to meet crop nutrient requirements without the use of synthetic fertilisers (Birkmose, 2007; Al Seadi, 2012). Any potential (usually minimal) losses of N during crop growth and biogas production (through leaching and/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. If the amount of N fixed by the legume component of an energy cropping system outweighs the N losses, a surplus of N in the CLN system would result and this may be used to fertilise other land where food crops are grown.

Digestate poses less risk of N leaching and N_2O emissions than the direct incorporation of crop residues, green manure or animal manure slurry (Moller and Stinner, 2009). Nitrogen loss to the atmosphere as ammonia in that study was about 10% with digestate (if not soil incorporated) versus 9% for undigested slurry and 7% for farmyard manure, but NH_3 is not a GHG.

World fertiliser production consumes over 1% of the world's energy needs and produces 1.2% of the world's GHG emissions (Wood and Cowie, 2004). The overall GHG footprint of a crop fertilised with digestate is smaller than when fertilised with manure or synthetic N fertiliser (Wulf *et al.*, 2006; Alburquerque *et al.*, 2012) Therefore, the combined effects of using the anaerobic digestion digestate to fertilise crops together with fossil fuel substitution for vehicles will contribute significantly towards reducing New Zealand's agricultural GHG footprint.

The CLN system proposes to use 'marginal' land, rather than land suited to high-value food production. There are numerous categories of marginal land in New Zealand (Lynn *et al.*, 2009). This study chose to focus on 'summer dry' marginal land (Renquist *et al.*, 2010; Trolove *et al.*, 2013) because one of the predicted outcomes of climate change is an increase in dry summers in eastern and northern areas of New Zealand (NIWA, 2013). Returns from growing biofuels on good arable land will likely be lower than from high-value food crops, but there are a number of situations where biofuels may give better returns and income stability than pastoral crops currently grown on 'summer dry' land (Kerckhoffs *et al.*, 2012).

The marginal land used by farmers for CLN bioenergy crops, while only using a portion of their land, can provide an additional source of income while diversifying risk. This would further increase energy self-sufficiency in the rural sector. The growing of crops is at a scale that farmers already manage and the finance required to build an anaerobic digestion plant is affordable by a large-scale farmer or cluster of farmers. There are also many niche situations where the CLN system can address specific environmental and/or economic issues in particular regions. These include nutrient-sensitive catchments where traditional livestock farming methods are called into question, such as around Lake Taupo (Environment Waikato, 2007); land infested with problem weeds that are toxic to livestock or herbicide resistant (Northland Regional Council, 2013); farms where distance from market or labour constraints may restrict traditional farming systems; or farms seeking an "environmentally friendly" market advantage. Furthermore there might be particularly high value propositions for locally-sourced biofuel under particular circumstances, such as in tourism areas, as already demonstrated in Queenstown (EECA, 2011).

Crops suitable for the CLN system

A broad review of crops likely to produce high biomass in New Zealand (Renquist and Kerckhoffs, 2012) identified a range of crop species suitable for the CLN system. The main requirement for bioenergy crops is their ability to produce a large amount of non-woody biomass free of soil, as the anaerobic digestion process does not break down lignin and soil contamination increases biogas plant maintenance. After screening several candidate species for use in the CLN project (Renquist *et al.*, 2010, Kerckhoffs *et al.*, 2011), the main focus was on field testing of forage sorghum (*Sorghum bicolor* (L.) Moench) , which can produce well on summer dry marginal land, and Jerusalem artichoke (*Helianthus tuberosus* L.), a crop with a high potential to produce above-ground biomass. Yields from two winter legumes, crimson clover and tickbean, for use within a rotation with sorghum were also measured. Maize is widely used in Europe for biogas production and was included in trials in the first year of this project as a well-studied benchmark for the biomass production of the newer species.

Crop performance and methane yield for the CLN system

Our past research showed that sorghum ('Jumbo' and 'Sugargraze') could yield 28-30 t DM/ha in Kerikeri with good soil water supply (Kerckhoffs *et al.*, 2012). However, it is well adapted to water deficit: following an early water deficit on summer dry land in Hawke's Bay sorghum out-yielded all other crops in the trial including maize, producing 18-21 t DM/ha (Kerckhoffs *et al.*, 2011). Crop model calibrations showing that sorghum is somewhat low-temperature limited in the regions south of Hawke's Bay (Renquist and Shaw, 2010); these regions are not consistently warm enough to get the benefit of sorghum's drought-tolerant properties. Jerusalem artichokes (grown in Hawke's Bay without water stress) yielded 16 t DM/ha if planted after mid-October and 31 t DM/ha if planted in September (Renquist and Kerckhoffs, 2012).

Both crop species produced the above yields on 66 kg mineralisable N/ha plus 100 kg fertiliser N/ha; there was no yield increase from supplying additional N. Sorghum grown with digestate yielded as well as sorghum grown with ammonium sulphate at the same rate of total N (data not shown). Winter legumes that could be used with summer annual species are crimson clover (yield 9.6 t DM/ha) and tickbean (18 t DM/ha) (Kerckhoffs *et al.*, 2012). Another promising legume, not evaluated in this study, is lupins (Vellasamy *et al*., 2000). As noted above, these legumes are an essential part of the CLN cropping system if summer annual species have high N requirements, since the legumes fix N that is returned via the digestate to fertilise these biomass crops.

Table 1 lists the biogas energy yields of Jerusalem artichoke and two sorghum cultivars. Dry matter yields have been converted to volatile solids by subtracting the ash content. The total yield of biomethane per hectare was calculated by multiplying the yield of volatile solids per hectare by the specific methane yields. These were directly measured in the laboratory under standardised conditions

(Amon *et al.*, 2007). The specific methane yields were 254 m^3 CH_4/t volatile solids for Jerusalem artichoke and 332 and 335 m^3 CH_4/t volatile solids for the two sorghums, 'Sugargraze' and 'Jumbo' respectively. The net energy yield values are assumed to be 70% of the total methane energy yield, which accounts for an assumed 30% internal energy consumption (as mentioned earlier).

Table 1: Net energy yield measured from three crops in Hawke's Bay, as biomethane volume and diesel fuel energy equivalent. VS = volatile solids.

Crop Species	Crop yield (t VS/ha)	Total yield (m^3 CH_4/ha)	Net yield (m^3 CH_4/ha)	Energy yield (GJ/ha)	Diesel equivalent (l/ha)
Jerusalem artichoke cv. Inulinz	14.46	3672	2571	87	2427
Sorghum cv. Sugargraze	19.76	6559	4592	156	4334
Sorghum cv. Jumbo	24.15	8091	5664	193	5346

The volumes of methane per ha are also shown in Table 1 as energy (GJ) per ha and as the volume of diesel with equivalent fuel energy, using a conversion factor of 0.944 litres of diesel per cubic meter of net methane yield (NZ Energy Data File, 2011).

Environmental benefits

The environmental benefit (in terms of GHG reduction) of substituting the net amounts of diesel fuel listed in Table 1 are 6.4, 11.4 and 14.5 t CO_2/ha/year for Jerusalem artichoke, 'Sugargraze' and 'Jumbo', respectively, assuming a GHG emission factor for diesel fuel of 73.25 kt CO_2/PJ. The DM yield of Jerusalem artichoke in research plots in 2012 was 1.9 times higher when the crop was planted earlier, so the GHG emissions benefit may be as great as that of sorghum. These biomethane yields are projections from the crop yields in research plots under Hawke's Bay climate conditions, so do not necessarily apply to New Zealand as a whole. That wider assessment is done in the final subsection of this section using regionally relevant crops.

Further environmental benefits of the CLN cropping system pertain to the substitution of crop N fertiliser (via digestate recycling). Since natural gas (NG) is used to make the fertiliser there is a dual saving of GHG emissions: 1) those from using the NG to produce synthetic fertiliser and 2) the N_2O emissions difference between using the synthetic fertiliser and using digestate (Moller & Stinner, 2009). Assuming an annual N application of 200 kg N/ha (requiring 300 m^3 of natural gas to make) 11.4 GJ/ha fossil energy can be saved each year, which reduces GHG by 0.15 t CO_2 equivalent/ha/year (West and Marland, 2002).

Model scenario: a biogas plant supplied by a group of farmers

A model scenario was developed to better understand the environmental benefit of producing biogas from crops, and to evaluate the economics of a biogas plant. It also acted as a platform to gain a practical understanding of issues such as logistics and soft benefits. The model scenario focused on the Lake Taupo region, where an additional driver for change to traditional livestock farming, particularly dairying, is nutrient capping (Environment Waikato, 2007). The case study consisted of CLN crops from 220 ha of land in order to supply enough biomass for a biogas plant of favourable scale. A group of 12 farmers is assumed, each dedicating some of the required crop land. This scale is modelled on a successful 12-farmer group in Margarethren am Moos, Austria (Figure 1) operating a biogas plant with 3,500 m^3 digester capacity supplied by crops from 220 ha of land. The New Zealand scenario assumed the use of a mix of crops, suitable for the central North Island (Table 2).

Table 2: Calculated biomass production and biomethane yields in a scenario using 220 ha of land near Taupo, North Island. VS = volatile solids.

	Area (ha)	DM yield (t/ha)	VS total per crop (t/year)	Net methane yield per ha (m^3CH_4/ha/year)	Net methane yield per crop (m^3CH_4/year)	% methane yield per crop
Jerusalem artichoke	90	20.0	1,600	3,161	284,480	30%
Triticale (x *Triticosecale* Wittm. ex A. Camus.)	80	16.0+	1,180	2,901	232,106	24%
Sorghum	30	20.0+	560	4,364	130,928	14%
Maize (*Zea mays* L.)	20	22.0+	420	4,969	99,372	10%
Crimson clover (*Trifolium incarnatum* L.)	130[1]	7.5[3]	900	1,623	211,050	22%
Total	220[2]	---	**4,660**	----	**957,936**	100%
Average (220 ha)		23.2	21.2	**4,354**		

[1] This 130 ha is counted twice, since winter legumes use the same land as the total of all annual crops.

[2] Total area for summer and perennial crops, but not inter-crops.

[3] Winter clover yield is added to each of the three annual species.

Table 2 gives dry matter yields per ha, estimated as long-term average DM yields for marginal land, based on previous research trials in Hawke's Bay. Some of the estimated yields were reduced from research trial yields using crop models (McCown *et al.*, 1996; Keating *et al.*, 2003); others are interpolated from limited results of trials in shallow soil and during drought years. Total yields of volatile solids are calculated from DM per ha and area per crop species. Note that the total summer (and perennial) crop area is 220 ha, but that all the annual crops are followed by a winter legume, which adds 7.5 t DM/ha to those annual yields.

The net methane yields per ha (i.e. after subtracting the 30% internal energy consumption) shown in Table 2 were calculated using specific biogas yield values for Jerusalem artichoke, triticale, sorghum, maize and crimson clover of 254, 281, 334, 338 and 335 m^3 CH_4/t volatile solids, respectively. These figures are based on the laboratory test results for Jerusalem artichoke and sorghum, and those for maize, clover and triticale are mean values from the large substrate atlas in the EU AGRO-BIOGAS database (Amon, 2008).

The total net production is 958,000 m^3 CH_4/yr. This is equivalent to 904,000 l diesel fuel/yr or 75,000 l diesel fuel for each of the 12 farms or 4,110 l diesel fuel/ha of

CLN cropping land. This amount of biogas energy would provide much of the energy needs of the wider Lake Taupo region, and is fully compatible with many other environmental goals such as GHG emission reduction and environmentally sound farm nutrient management. The biofuel yield calculation is based on crop yields on marginal land rather than prime cropping land. Initial N fertiliser needs may be higher on marginal land, but N is recycled thereafter.

While energy yields from crops in warmer regions north of Taupo may be higher than those calculated for this scenario, an average value for summer dry land across all New Zealand cropping regions could be expected to be less than the 4,110 l diesel per ha from the scenario.

The biomass crop in the Taupo scenario in Table 2 which may prove to have the greatest environmental benefits is the perennial Jerusalem artichoke. The summer annuals, followed by a winter legume, have a very high biomethane yield potential due to their high specific methane yields and from having the added winter legume yield. However, these options do involve more farming inputs that use fuel. Summer annuals also have higher nutrient needs, but these would be fully met by recycling the nutrients in the digestate from previous crops, including the winter legume.

Model scenario economics

Determining an accurate cost of production for biogas from a CLN-type scheme is rather difficult, as the cost can be case specific. While economies of scale for digestion equipment would favour large digestion facilities, transport 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 New Zealand conditions. The choice of a 12 farmer group biogas plant based on 220 ha of CLN cropping land in the model scenario used in this study is therefore a good compromise between the opposing drivers.

Since there are no large-scale rural biogas plants operating in New Zealand, the cost structure of the model scenario had to be adapted based on data from the thousands of rural biogas plants working overseas. Such data are available from the KTBL (2012) online database for Germany and Austria (Amon, 2008). These databases provide cost of feedstock production and also the cost of anaerobic digestion plant construction and operation. For early adopters of the CLN concept in New Zealand it will be important to determine if the costs in the overseas databases match those for components sourced in New Zealand, since the prices of equipment for digesters built by early New Zealand adopters will not reflect those in high-volume, competitive markets.

Grower profit potential using the new perennial species Jerusalem artichoke is based on low production costs compared with maize thus creating the opportunity to make better use of lower value land. For the high-level analysis, biomass prices were assumed as an average $155/t DM, lower than maize silage feed, reflecting the difference in agronomic effort for the CLN crops. At that price, average gross return per ha would be $3100/ha if the yield of Jerusalem artichoke was that used in the model estimate, but $3875/ha if Jerusalem artichoke can yield 25 t DM/ha (indicated by research plot yields exceeding 30 t DM/ha).

To process the feedstock from 220 ha CLN cropping land, a digester facility with a 3,500 m^3 main fermenter would be required. Capital and operating expenses for a 3,500m^3 fermenter facility were taken from KTBL (2012), based on several thousand biogas plants operational on farms in Germany. The capital costs included the digester, and digestate storage facility, biogas upgrading plant, gas compressor/refuelling facility and controls. Investment costs (excluding land) were assumed to total $1.9M, or $181,000/yr assuming a 20 year useful life of the facility. At 9% interest rate, financing costs would total $86,000/yr, assuming full repayment of the facility over its useful life time. Other operational costs such as maintenance, consumables, insurance and labour were assumed to total $106,000/yr.

Using this approach the cost of renewable methane production can be calculated as $33/GJ or $1.20/l diesel fuel equivalent. This includes the cost of feed stock provision following the CLN approach plus the levied capital and operating costs of a plant required to digest the feedstock and purify and compress the fuel to be fit for use in a gas powered vehicle. It should be noted that in this scenario, equipment and hardware costs represent less than a quarter of the cost of renewable fuel production. Fluctuations in operational costs, and most importantly feedstock costs, will have a much larger impact on the bottom line of the model scenario. As a consequence it can be assumed that the presented model is also very sensitive to achievable crop yields.

A retail diesel price of $1.50/l is equivalent to $42/GJ. It can therefore be said with confidence that for some applications the difference between $33/GJ projected above for biogas methane and $42/GJ for diesel can justify the conversion cost and impracticalities associated with the operation of gas-powered vehicles. With petroleum cost likely to increase in the future, it is also likely that the financial attractiveness of biogas vehicle fuel is going to increase.

This simplified analysis is not suitable for use for investment decisions. It does 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.

The potential of biofuel crops to supply New Zealand rural fuel requirements

This research involved quite a different approach than a calculation to scale up the results of the 12-farmer Taupo scenario across the whole country. Rather, it used the LENZ database (Leathwick *et al.*, 2003) to identify land with a mean slope of 0-9° and with >50mm annual water stress. The identified total land area was 4.7 million ha. The New Zealand land base suitable for biogas or other biofuel production is clearly a great asset, and these areas do not include the steeper land that could potentially be used for woody biomass species when the ‘wood to biofuel’ conversion technologies mature.

Our model analysis indicated that biofuel crops grown on 5% of the marginal (summer dry) arable land could supply biomethane energy equal to more than twice the diesel fuel requirements of the New Zealand Agriculture Sector in 2010 (NZ Energy Data File, 2011). This finding was very positive, considering how conservatively the biomethane yield was calculated.

A summer-sorghum / winter-wheat rotation was used as representative of a C_3-

C_4 crop rotation in the northern half of the North Island, and perennial lucerne was used as a crop that is representative of a C_3 crop for the summer dry areas in the rest of New Zealand. The APSIM crop model (McCown *et al.*, 1996) was used to estimate DM yields for different environments. 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. Net biomethane yields were based on 30% internal energy consumption, as previously described.

The net methane yield from 5% (235,000 ha) of the 4.7M ha of marginal summer dry land would be 580M m^3 CH_4/year equal to 548M litres of diesel/year equal to 19.7 PJ/yr. A full description of the modelling and this bioenergy calculation is presented in Trolove *et al.* (2013).

There is a significant environmental benefit from rural use of this biomethane in place of fossil fuel. Assuming 73.25 kt CO_2 /PJ diesel, this would equal a GHG emission reduction of 1.44M t CO_2 from fuel substitution alone. These benefits could easily be increased as more land could be used for CLN cropping if external users provide a demand for additional renewable petroleum substitute.

Processing the biomass from bioenergy crops grown on just 5% of the identified marginal land with a CLN biogas cropping system would require 570 plants of the size outlined above for a 12-farmer group. It is very feasible to build this number of plants during a time frame of about a decade, when compared to successful biogas programmes overseas. In Germany, there are over 7000 farm biogas plants operational on a land base not much larger than that of New Zealand; these were built during the last decade. Construction of these biogas plants supplying rural sector energy needs could create hundreds of new jobs and, based on 2012 figures, would reduce New Zealand's petroleum import bill (current account deficit) by over half a billion dollars annually, even if it is assumed that most petroleum is imported as crude oil and not as finished product. In terms of rural benefits, a new industry based on biomethane production from bioenergy crops has much to offer.

Conclusions

The CLN cropping system focuses on purpose-grown bioenergy crops to produce on-farm biogas using anaerobic digestion technology, as the most suitable 'rural scale' technology to generate biofuel. Such a cropping system is a promising way to increase farming resilience, both by fossil fuel substitution and by replacing N fertiliser use. Even if only 5% of 'summer dry' arable land is planted in biofuel crops, the CLN system could supply energy greater than the engine fuel needs of the New Zealand agricultural sector, without utilising high-value cropping land for energy production. This could provide another source of income for farmers and spread their financial risk.

Biomethane is a versatile fuel with many uses, the most high-value of which is for vehicle fuel. Rural anaerobic digestion can utilise a wide range of bioenergy crops, and the appropriate crop mix can be tailored to fit each individual situation. Sorghum and Jerusalem artichoke were identified as the most promising crop species to generate sustainably high net methane yields on marginal lands. Using whole-crop biomass, anaerobic digestion yields at least three times more engine fuel than if a crop was grown on the same land for biodiesel. Rural situations where growing crops for biomethane may be particularly beneficial include: drought-prone areas and other areas where traditional farming methods are increasingly called into question, isolated communities with high fuel or electricity prices and for growers of organic/eco-friendly products, where GHG mitigation has marketing value.

The CLN system offers one of the best approaches to mitigate New Zealand's agricultural GHG emissions, enhancing New Zealand's 'clean and green' image internationally and reduce its vulnerability in a global fuel crisis.

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