Methane production from biofuel crops grown in New Zealand

L.H.J. Kerckhoffs[1], S. Trolove[2], S. Heubeck[3] and R. Renquist[4]
[1] Massey University, Private Bag 11222, Palmerston North 4442
[2] The New Zealand Institute for Plant & Food Research Ltd, Private Bag 1401, Havelock North 4157
[3] National Institute of Water and Atmospheric Research, PO Box 11115, Hamilton
[4] Bioenergy Cropping Solutions Ltd, 14 Springdale Grove, Palmerston North 4410

Abstract

On-farm biomethane production from biofuel crops is well established at a large scale in Europe, but there is limited data available in New Zealand. A research trial was established to test components of a biofuel system under New Zealand conditions within a closed-loop nitrogen bioenergy production system (CLN). Forage sorghum yields of 25 t DM/ha were achieved with 100 kg N/ha applied on a moderately low N soil (66 kg mineralisable N/ha) and there was no increase in yield from applying additional N. Sorghum grown with digestate from an anaerobic digester yielded the same as sorghum grown with ammonium sulphate applied at the same rates of total N. Jerusalem artichoke was identified as a promising perennial biogas crop with trial methane yields of 3672 m^3 CH_4/ha, while forage sorghum showed particular potential for summer dry land. Methane yields of 6559 m^3 CH_4/ha and 8091 m^3 CH_4/ha were recorded for the sorghum cultivars Sugargraze and Jumbo respectively. These methane yields are similar to those from biomass crops grown and tested under more intensive conditions in Europe. Crimson clover is superior to white clover as a winter legume (mid-May to mid-November) for DM production in a CLN system, yielding 9.6 t DM/ha compared with 5.3 t DM/ha for white clover.

Additional keywords: sorghum, Jerusalem artichoke, crimson clover, anaerobic digestion, digestate, biogas, renewable energy, closed-loop nitrogen system

Introduction

Approximately 50% of greenhouse gas (GHG) emissions in New Zealand come from agriculture (WRI, 2010). There is little that can be done about emissions produced from grass-fed sheep and cattle, but considerable savings can be achieved by reducing emissions from fossil fuels used by the rural sector (Murphy *et al.*, 2009). Renquist *et al.* (2010), Renquist *et al.* (2013) and Trolove *et al.* (2013) discussed the possibilities of replacing fossil fuels with fuel produced by anaerobic digestion (AD) of crops in a Closed-Loop Nitrogen (CLN) bioenergy production system. In such CLN systems, crops that produce a large amount of biomass are grown on marginal land (thus not competing with food production), then anaerobically digested, with all the nutrients remaining in the biogas digestate. This digestate is then applied back onto the field where the crops were grown, thus closing the nitrogen (N) loop. A model study applying field trial results to a New Zealand-wide scale indicated that if CLN biomass crops were grown on only 5% of the 'summer dry' arable land, they could supply 19.7 PJ per year of fuel energy, more than twice the current annual diesel fuel needs for transport of New Zealand agriculture (Trolove *et al.*, 2013).

Kerckhoffs *et al.* (2011) discussed preliminary trials to identify crops for biofuel production on marginal land in New Zealand. The crops identified were: (1) sorghum (*Sorghum bicolor* (L.) Moench), which produced well on land that is prone to summer moisture stress; and (2) Jerusalem artichoke (*Helianthus tuberosus* L.), which is a high yielding perennial crop that would be beneficial in areas where crop establishment is risky. This paper presents new dry matter (DM) yield data, and whether yields can 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 Jerusalem artichoke, multiple cuts very early in the summer yielded equal or greater total biomass (Rawate and Hill, 1985). This paper also reports the specific methane yields (m^3 CH_4/ha) for sorghum and Jerusalem artichoke from experiments using direct measurements to assess the production of biogas (biomethane) from crops grown in New Zealand.

One of the crucial aspects of the CLN system is 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 are recycled to the next crop by applying the liquid from the anaerobic digester to the soil prior to planting. This practice is already widespread in several EU countries and several research papers have examined the underlying science (Whelan *et al.*, 2009; Alburquerque *et al.*, 2012) on issues such as efficacy, quality control (Lukehurst, 2009; Al Seadi, 2012) and ammonia (NH_3) volatilisation (Wulf *et al.*, 2006; Nyord *et al.*, 2008; Moller and Stinner, 2009). However it is necessary to test the efficacy of digestate in NZ soils and climate. The crop chosen to test the use of digestate was sorghum, since N recommendations for sorghum are high. Recommendations as high as 500 kg N/ha for a 20 t DM/ha crop are not uncommon, requiring large volumes of digestate. This large volume would require several applications. Therefore an important component of the system to test is whether large yields of sorghum can be produced with less N, and how the plant-availability of N in anaerobic digestate compares with chemical fertiliser. A large incentive for finding alternative N fertiliser sources is the fact that an estimated 1.2% of global total energy consumption is used to synthesise artificial N fertilisers (Wood and Cowie, 2004). The trial site for the N tests was a deep, fertile soil with high water-holding capacity, amenable to high yields. It was important to determine whether digestate could supply N at a rate sufficient to produce high yields.

In addition, potential (but small) losses in N within the CLN system could be more than replaced by growing an additional CLN feedstock on part of the farm, either a perennial legume such as lucerne (*Medicago sativa* L.) or a winter legume crop between annual crops. Renquist *et al.* (2010) identified that crimson clover (*Trifolium incarnatum* L.) should be investigated as a winter legume crop. Legumes are predominantly used for animal feed in New Zealand, but crimson clover is hairy and relatively intolerant of hard grazing. It is likely, but is unknown, that crimson clover should grow well under New Zealand conditions and produce a large amount of high quality biomass over autumn-spring. This legume would complement biomass production from either sorghum or Jerusalem artichoke, and would have the advantage of supplying additional nitrogen into the CLN system. This extra N would more than replace N losses due to volatilisation of the applied ammonium, or any leaching of ammonium that has converted to nitrate. The digestate could also be used to further enhance the N fertility of some other areas of the farm.

Materials and Methods

Experiment 1: Growth of forage sorghum and Jerusalem artichoke

Field trials were located at the Plant and Food Research site on Lawn Road in Hastings, New Zealand (39° 36’ S; 176° 54’ E). The soil at this site is an imperfectly drained silt loam with no limitations to rooting depth.

Jerusalem artichoke (*Helianthus tuberosus* cv. Inulinz) was planted by hand on 9 November 2010 at 6.3 seed pieces/m^2, 40 × 40cm spacing. The seed source was tubers dug from the previous year’s experiment. Two cultivars of forage sorghum [*Sorghum bicolor* × *Sorghum Sudanese* cv. Jumbo; *Sorghum bicolor* cv. Sugargraze] were sown on 8 December 2010. Seed was sown at 1 cm depth at a density of 130 seeds/m^2.

Two rates (100 and 200 kg N/ha) of nitrogen fertiliser were applied as ammonium sulphate. Fertiliser was applied by hand before sowing. The main experiment was a randomised complete block design with four replicates; plot size was 2.4 m × 8 m. Weed control in the Jerusalem artichoke plots was achieved by a post-planting application of the herbicide Stomp Xtra® (3 l/ha). Follow-up hand hoeing was done on two occasions during the first four weeks of each planting. No further weed control was used. Weed control in sorghum involved a post-planting application of the herbicide Alachlor® (4.75 l/ha) followed with a post-emergence application of Basagran® (1.75 l/ha). Irrigation was applied on three occasions (3 and 29 November 2010; 2 February 2011; 30 mm each, as indicated by a water use model) to maintain optimal plant performance.

The aim was for the sorghum to be harvested at around the ideal time for making silage (i.e. 30 to 38 %DM). Quadrats (1.035 m^2) of sorghum were harvested on 28-30 March 2011; a few weeks after plants had lodged following very strong winds. Stems were counted (which in the cv. Jumbo included several thin tillers) and the stem lengths measured. A DM sub-sample from each quadrat was dried for two days at 80°C.

Jerusalem artichoke two-cut system

For Jerusalem artichoke, another objective was to compare a two-cut system (one harvest mid-season and one harvest near the end of the growth season) with the standard single harvest near the end of the growth season (4-6 April, 2011).The first cut, for the two-cut system, was taken on the 22 February, 2011; tops were harvested with 10 cm stalks left. Jerusalem artichoke quadrats were 1.6 m × 0.8 m (1.28 m^2) containing 8 plants. The total number of plants, stems and side branches (defined as stems <18 mm diameter) were recorded, and plant DM measured. The main date of Jerusalem artichoke harvest was 4-6 April, 2011.

Methane yield

Silage sample harvests to assess in-vitro biogas and methane yields 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 29 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 the Department of Sustainable Agricultural Engineering, University of Natural Resources and Applied Life Science (BOKU), Vienna for direct measurement of methane production. Their laboratory has a large number of small-scale anaerobic digesters and a proven protocol (Amon *et al.*, 2007 a, b) for measuring biogas and methane yield. Samples were also analysed at Massey University (Palmerston North) for indirect determination (by empirical calculation) of methane production (Kerckhoffs *et al.*, 2011).

Experiment 2: Jerusalem artichoke planting date comparison

A follow-up experiment in 2011-12 compared two spring planting dates, similar to the calendar date in Experiment 1 versus two months earlier, 9 September 2011. Other procedures were the same as the 2010 planting. Only N fertiliser was applied, at a rate of 100 kg N/ha.

Experiment 3: Digestate as N fertiliser source for sorghum

To help assess the amount of N supplied by the digestate, the amount of N in the soil was reduced by growing a crop of maize in the previous season to which no N was added. All above ground biomass except for approximately 5 cm stubble was then removed from the site. This gave the soil chemical properties as outlined in Table 1. From this analysis it was assumed that P, K, Mg and Ca were not limiting plant growth so none of these elements were supplied as fertiliser. Digestate was compared with ammonium sulphate at the same rates of N (100 and 200 kg N/ha). The soil was cultivated with a power harrow to a depth of approximately 20 cm.

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 of the 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 0.66 kg N/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/m^3 (FNR, 2005), although the N concentration of the feedstock can vary widely. Both the digestate and ammonium sulphate were applied by hand to the soil surface and then mixed in with a power-harrow after three days when the soil from the digestate treatment had dried enough to be power harrowed.

A late-maturing sweet sorghum cultivar (*Sorghum bicolour* cv. Sugargraze) was sown on 13 December 2010. Seed was sown at approximately 1 cm depth with an 8-row seed drill in rows 15 cm apart, at a density of 130 seeds/m^2. The experiment was a randomised complete block design with four replicates along-side the main trial; plot size 2.4 × 8 m. Quadrats (1.035 m^2) were harvested on 28–30 March, 2011.

Table 1: Chemical properties of the soil used for growing sorghum and Jerusalem artichoke at Plant and Food Research site on Lawn Road in Hastings, New Zealand (sample date September 2011).

pH	Olsen-P	CEC	Ca	Mg	K	Na	Anaerobic min. N
	(µg/ml)	(me/100 g)					(kg/ha)
5.5	40	21	10.7	2.4	0.9	0.1	66

Experiment 4: Crimson clover trial

For the crimson clover trial, an area of permanent lawn was sprayed with glyphosate (2 l/ha). After the grass died, seed of crimson clover (*Trifolium incarnatum*) and white clover (*Trifolium repens* L. cv. Huia) was sown on 4 May, 2010. Seed was drilled just below the soil surface (0-1 cm depth), then the trial was harrowed and rolled with a Cambridge roller. *Rhizobium* spp. inoculum was used with both legumes. Crimson clover was sown at 500 seeds/m^2 and white clover at 315 seeds/m^2. There were four 7.0 m^2 plots of each treatment. Quadrats (0.9 m^2) were cut from each plot at approximately 2 cm above ground level on 12 November 2010 and DM yields measured.

Results and Discussion

Experiment 1: Growth of forage sorghum and Jerusalem artichoke

Sorghum produced significantly more above-ground biomass than Jerusalem artichoke in 2010-11 (Table 2). While the Jerusalem artichoke above-ground yield in Experiment 1 was 16 t DM/ha, the yield in the Experiment 2 early planting of Jerusalem artichoke was nearly double that. This indicates that Jerusalem artichoke yield in this trial was not at full potential in terms of either DM or methane, for purposes of comparison with sorghum.

Concurrently with this trial, Jerusalem artichoke experiments gave preliminary indications of the range of successful adaptation of Jerusalem artichoke cropping for biomass in New Zealand. Where winters are as mild as Kerikeri, there is inadequate chilling of tuber buds to grow Jerusalem artichoke as a perennial. Trials in Canterbury and Southland showed Jerusalem artichoke is well adapted and the longer daylength at high latitudes is an advantage. An early planting allows the crop to grow for about 200 days prior to shoot senescence, which appears to be triggered by short days in order to favour tuber growth (Kays and Nottingham, 2008). Unlike sorghum there is no clear requirement for a growing season as warm as that of Hawke's Bay.

Table 2: Crop yields (t DM/ha), N content (%) and shoot N uptake (kgN/ha) of Jerusalem artichoke and sorghum cultivars.

	Sorghum 'Jumbo'	Sorghum 'Sugargraze'	Jerusalem artichoke-shoot 'Inulinz'	P	LSD (5%)
Yield	27.0	22.1	16.3	<0.001	4.9
N content	0.97	1.11	1.18	0.099	0.20
N uptake	251	234	196	0.031	41

The mean DM yield of cv. Jumbo was not different to that of cv. Sugargraze (Table 2). Shoot N uptake at harvest time by the three crop species had the same pattern as crop yield. Shoot N of Jerusalem artichoke is less indicative of crop removal of N than for sorghum. While the mass of tubers is substantial and might seem to represent additional crop removal, much of the N and DM in tubers are likely to have been recycled from shoots (Kays and Nottingham, 2008). Another indication that crop removal of N is lower in Jerusalem artichoke than sorghum is that a century of empirical findings and some research with Jerusalem artichoke (Kays and Nottingham, 2008) have lead to fertiliser N rate recommendations that are less than a third of those for sorghum.

The shoot DM yield of early-planted Jerusalem artichoke is likely to prove similar to that of sorghum so there should be no incentive to harvest tubers from a Jerusalem artichoke biomass crop, other than the near-surface tubers than are lifted by the shallow harrowing recommended for spring control of winter weeds in a perennial planting. The drawbacks from a full tuber harvest include the increased energy required to harvest them and the large amount of soil disturbance which increases soil CO_2 emissions and the risk of soil erosion on marginal land. There was no increase in DM yield from applying an additional 100 kg N/ha (Table 3) nor was there any significant plant type by fertiliser rate interaction.

The additional 100 kg N/ha did increase the N content of the crops and N uptake (Table 3), 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 or volatilisation when the digestate is returned to the same crop area.

Table 3: Crop yields (t DM/ha), N content (%) and shoot N uptake (kgN/ha) of sorghum and Jerusalem artichoke for two N fertiliser treatments (averaged across the three cultivars/crops tested).

	Fertiliser rate (kgN/ha)			
	100	200	P	LSD (5%)
Yield	22.0	21.6	0.838	4.7
N content	0.96	1.21	0.005	0.16
N uptake	205	249	0.013	33

Jerusalem artichoke two-cut system

Shoot biomass of Jerusalem artichoke increased by 26% between 22 February (12.9 t DM/ha) and 5 April, 2011 (16.3 t DM/ha), when plants were left uncut on the first date. The %DM increased significantly for both harvest dates (13.6% to 24.2% respectively). The trial showed no significant re-growth in plots that were harvested on 22 February, 2011. This may have been because the first harvest date in the two cut system was too late in the season when translocation of sugars was directed downwards to the tubers, rather than upwards to produce new shoots; or alternatively the stems may have been cut too low, leaving insufficient leaf area to enable continued growth. For that reason a second test of the two-cut approach was made in an adjacent trial. This experiment used a second year Jerusalem artichoke planting with much higher stem population of 134 per m^2 (80 days after shoot emergence) and likely to be more suitable for two harvests. The two-cut plots were cut early (14 December 2011) with stems left 30 cm tall. The crop was left to re-grow until May. The two cuttings each yielded 5.7 t DM/ha (11.4 t DM/ha total), while the plots with a single cut mid-March 2012 yielded 25.6 t DM/ha (unpublished). Clearly, cutting a Jerusalem artichoke crop twice is detrimental to the aim of maximising DM yield. The %DM is also very low in February, 2011, let alone December 2010, posing an issue if the biomass is to be ensiled.

Methane yield

The ensiling methodology was successful and the ensiled samples arrived in good condition. Analyses at BOKU provided expected yields of biogas and methane (Table 4).

Table 4: Biogas and specific methane yields (direct laboratory measurement; m^3/tVS) during digestion of ensiled samples measured at BOKU, Vienna. The standard deviations (SD) among 6 replicates are shown after each mean. VS is volatile solids.

Crop species and cultivar	Biogas yield (m^3/tVS)	CH_4 yield (m^3/tVS)
Jerusalem artichoke cv. ‘Inulinz’	392 (26.6)	254 (15.4)
Sorghum cv. ‘Sugargraze’	544 (47.5)	332 (33.4)
Sorghum cv. ‘Jumbo’	535 (49.4)	335 (34.1)

The specific methane yields in the BOKU analyses were applied to the biomass yields (Table 2) to quantify the total methane yield potential per ha (Table 5). Dry matter yield was the most influential factor in gas yield, which favoured sorghum cv. Jumbo. If the higher Jerusalem artichoke DM yield potential (as mentioned before) is taken into account, the methane yield of Jerusalem artichoke will also likely be higher than in this trial.

The direct biogas and methane measurements support the previous indirect method of calculation using tissue composition (Kerckhoffs *et al.*, 2011). Sorghum methane yields were approximately 10% higher than those calculated by Kerckhoffs *et al.* (2011).

Experiment 2: Jerusalem artichoke planting date comparison

The findings in this experiment enabled the interpretation of Experiment 1 results to be updated. By planting in September, rather than November (or even October, as shown in an unpublished 2010-11 Jerusalem artichoke experiment, although this result does have significant implications for the calculated methane yield of Jerusalem artichoke presented here), the dry mass yield was very much higher, 31 t DM/ha.

Table 5: Total yield of methane (m^3 CH_4/ha) for Jerusalem artichoke and two sorghum cultivars tested.

Species and cultivar	Specific methane (m^3/ tVS)	Dry Mass (t DM/ha)	% Ash	%Volatile solids	Vol. solids (tVS/ha)	Total yield (m^3 CH_4/ha)
Jerusalem 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

Volatile solids (VS; the biomass fraction that can be converted to methane) = DM *minus* ash. Total CH_4 yield = specific methane × tVS/ha.

Experiment 3: Digestate as N fertiliser source for sorghum

The 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 6). The large yields of biomass with a modest rate of N applied (100 kg N/ha), as digestate or ammonium sulphate, plus a small amount of soil available N (66 kg N/ha of mineralisable N), suggests that sorghum does not require extremely high N fertiliser and is a suitable crop for biomass production in the CLN system.

Table 6: Sorghum yield (t DM/ha), N content (%) and N uptake (kgN/ha) for the digestate trial (Experiment 3).

Variable effect	Yield	N content	N uptake
Digestate	24.8	0.79	195
$(NH_4)_2SO_4$	25.1	0.96	237
100 kgN/ha	24.9	0.75	185
200 kgN/ha	25.1	1	247
Significance (P)	0.926	0.028	0.035
LSD	5.4	0.017	44

Nitrogen uptake in the ammonium fertilised plots was 10-32 kg/ha 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 mineralisable N test underestimated the amount of N that would be mineralised during the warm summer conditions (Curtin and McCallum, 2004). A much better measure of N availability in the soil is the plants themselves. Nitrogen uptake in the ammonium-fertilised 100 kg N/ha treatment was approximately 200 kg N/ha, which is very similar to that taken up by crops in the 100 kg N/ha treatment in the main trial (Table 3). The data suggest that 'Sugargraze' grown with 200 kg N/ha as ammonium sulphate took up 78 kg N /ha more into the shoots than the 100 kg N/ha (Table 2). 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 N/ha 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 (83% of which was readily available for plant uptake), sorghum grown with digestate took up 82% as much N as those grown with ammonium sulphate (Table 6). One conclusion may be that sorghum took up all of the immediately available N from the digestate and none of the slowly available N; however it is more likely that there was some volatilisation losses of the ammonium N from the digestate as NH_3 (which could be smelt for two to three days following the application) and some N supplied by mineralisation of the digestate.

The aspect of NH_3 volatilisation from digestate has been well-studied, as an extension of research on manure management (Van der Meer, 2008). 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.*, 2009) and effects on C and N dynamics in soils (Alburquerque *et al.*, 2012). While it will be difficult to keep 100% of the NH_3 within the CLN system, commercial digestate application technologies have been developed that minimize volatilisation losses. Of the methods researched, soil injection is usually the best (Wulf *et al.*, 2006) and of several injector types the high pressure trailing shoe type was the most effective, reducing NH_3 losses to <3% of total N (Nyord *et al.*, 2008). Losses of N from the CLN system via volatilisation of NH_3 following digestate application cannot entirely be avoided, but appropriate technology selection will help to minimise these losses significantly.

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. Moller 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 (see acknowledgements), 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.

Experiment 4: Crimson clover trial

Crimson clover yielded almost twice as much as white clover (9.6 versus 5.3 t DM/ha, P=0.018; 24 versus 13 %DM, P=0.005), making it a better option as a biofuel crop. While crimson clover is only a single cut crop so not suitable for repeated grazing, neither is the standard winter cover crop Italian ryegrass always grazed. Either can be ensiled, but crimson clover is much higher yielding and also easier to ensile due to its higher %DM. In addition to these advantages it would supply the CLN system with additional N and (as broadleaf) facilitate targeting grass weeds with selective herbicides. This finding of high winter legume yield within the CLN system with sorghum is a further example of the advantages of the mild New Zealand winter climate over those in much of North America and Europe.

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 straightforward option for compensating for 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 t DM/ha, which (assuming a shoot N concentration of 2.6%; Evers and Parsons, 2010), would supply 250 kg N/ha.

In the worst case scenario, the most N that could have been lost by volatilisation is 42 kg N/ha (the difference in N uptake between the ammonium sulphate and digestate treatments, see Table 6). So the N supplied by a winter crop of crimson clover would supply six times this amount, thus providing extra N that could be used to fertilise other crops. The obvious way to offset N losses within the CLN system is to replace lost N with N fixed by legumes.

Conclusions

High yields for sorghum grown in good conditions were consistent with previous observations. This research found that high yields can be achieved with low rates of N fertiliser (100 kg N/ha) and that more than 80% of the N in digestate was available to the crop within the growing season. Measured methane production rates were 3672 m^3 CH_4/ha for Jerusalem artichoke (based on a less than full potential DM yield), 6559 m^3 CH_4/ha for sorghum cv. Sugargraze and 8091 m^3 CH_4/ha for sorghum cv. Jumbo, which are similar to those from biomass crops grown and tested in Europe. The potential contribution of compressed liquid biomethane as a rurally-produced and utilised fuel, unlike first-generation liquid biofuels from crop oils and sugars, is very promising.

Acknowledgements

Funding for this research came from the Ministry of Agriculture and Forestry (MAF; now Ministry for Primary Industries, MPI) through the Sustainable Land Management for Climate Change (SLMACC) funds administered by the New Zealand Foundation for Research Science &Technology (FRST).

Brian Rogers and Nathan Arnold are thanked for technical assistance in field trials at Plant & Food Research (Lawn Rd); John de Ruiter (Plant & Food Research) for advice on ensiling techniques. Pioneer/Genetic Technologies Ltd, Pacific Seeds Pty Ltd and Inulinz Ltd are also thanked for supplying the seed; CSI for supplying the digestate. Thanks also to our collaborators at BOKU (Department of Sustainable Agricultural Systems/Division of Agricultural Engineering) in Vienna, in particular Drs Thomas Amon and Alexander Bauer.

References

Alburquerque, J.A., de la Fuente, C. and Bernal, M.P. 2012. Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils. *Agriculture, Ecosystems and Environment* 160: 15-22.

Al Seadi, T. 2012. Quality of digestate used as biofertiliser. Quality of digestate used as biofertiliser. Task 37 Workshop, Biogas in the loop of recycling. IEA Bioenergy. Retrieved on 20 October 2012 from http://www.iea-biogas.net/_content/publications/publications.php.

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K. and Gruber, L. 2007a. Biogas production from maize and dairy cattle manure. *Agriculture, Ecosystems and Environment* 118: 173-182.

Amon, T., Amon, B., Kryvoruchko, V., Machmüller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Pötsch, E., Wagentristl. H., Schreiner, M. and Zollitsch, W. 2007b. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresource Technology* 98: 3204-3212.

Curtin, D. and McCallum, F.M. 2004. Biological and chemical assays to estimate nitrogen supplying power of soils with contrasting management histories. *Australian Journal of Soil Research* 42: 737-746.

Evers, G. W. and Parsons, M. J. 2010. Nitrogen partitioning in arrowleaf, crimson, rose, and subterranean clovers without and with defoliation. *Crop Science* 50: 1562-1575.

FNR 2005. Ergebnesse des Biogas-Messprogramms - Results of the Biogas monitoring program. Technical monitoring report. FNR, Guezlow, Germany. 163 pp.

Kays, S.J. and Nottingham, S.F. 2008. Biology and chemistry of Jerusalem artichoke: *Helianthus tuberosus* L. CRC, Boca Raton. 478 pp.

Kerckhoffs, L.H.J., Shaw, S., Trolove, S., Astill, M., Heubeck S. and Renquist, R. 2011. Trials for producing biogas feedstock crops on marginal land in New Zealand. *Agronomy New Zealand* 41: 109-123.

Lukehurst, C.T. 2009. Developing the use of digestate in the UK (part of PROBIOGAS project EIE/04/117/S07.38588, presented at a seminar in Jyvaskyla, Finland). IEA Bioenergy Task 37, IEA Bioenergy, European Commission.

Moller, K. and Stinner, W. 2009. Effects of different manuring systems with and without biogas digestion on soil mineral nitrogen content and on gaseous nitrogen losses (ammonia, nitrous oxides). *European Journal of Agronomy* 30: 1-16.

Murphy, J., Braun, R., Weiland, P. and Wellinger, A. 2009. Biogas from energy crop digestion. Task 37 - Energy from Biogas and Landfill Gas. IEA Bioenergy. European Commission. 19 pp.

Nyord T., Sogaard, H.T., Hansen, M.N. and Jensen, L.S. 2008. Injection methods to reduce ammonia emission from volatile liquid fertilisers applied to growing crops. *Biosystems Engineering* 100: 235-244.

Rawate, P.D. and Hill, R.M. 1985. Extraction of a high-protein isolate from Jerusalem artichoke (*Helianthus tuberosus*) tops and evaluation of its nutritional potential. *Journal Agricultural Food Chemistry* 33: 29-31.

Renquist, R., Trolove, S., Shaw, S., Astill, M., Heubeck, S., McDowall, C. and Kerckhoffs, L.H.J. 2010. Biomass for biofuel with closed-loop N supply grown on marginal land. *In*: Farming's future – Minimising footprints and maximising margins. Eds L.D. Currie and C.L. Christensen. Occasional Report No. 23, pp. 459-471. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Renquist, R., Heubeck, S., Trolove, S. and Kerckhoffs, L.H.J. 2014. Closed-Loop N Cropping System: new land uses to make rural biofuel. *Agronomy New Zealand* 43 (in press).

Trolove, S., Kerckhoffs, L.H.J., Heubeck, S., and Renquist, R. 2014. The potential of anaerobically digested crops to supply New Zealand rural fuel requirements. *Agronomy New Zealand* 43 (in press).

Van der Meer, H. 2008. Optimising manure management for GHG outcomes. *Australian Journal of Experimental Agriculture* 48: 38-45.

Whelan, M.J., Everitt, T. and Villa, R. 2009. A mass transfer model of ammonia volatilisation from anaerobic digestate. *Waste Management* 30: 1808-1812.

Wood, S. and Cowie, A. 2004. A review of greenhouse gas emission factors for fertiliser production. Task 38. IEA Bioenergy. European Commission. 20pp.

WRI 2010. Climate Analysis Indicators Tool (CAIT Version 7), World Resources Institute, Washington DC. Retrieved on 20 August 2014 from http://cait.wri.org.

Wulf, S., Jager, P. and Dohler, H. 2006. Balancing of greenhouse gas emissions and economic efficiency for biogas-production through anaerobic co-fermentation of slurry with organic waste. *Agriculture, Ecosystems and Environment* 112: 178-185.