Trials for producing biogas feedstock crops on marginal land in New Zealand

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Abstract

Substituting fossil fuels with biofuels has been identified as one of the most feasible steps to reduce the agricultural greenhouse gas (GHG) footprint in New Zealand (NZ). Renewed interest in purpose-grown biomass crops in this context also stems from concern about the security of rural transport fuel supply and national transport fuel security. This research is on a novel cropping system for producing biogas featuring a closed-loop nitrogen (N) recycling system (termed CLN) for use on NZ marginal land. The biomass conversion technology, anaerobic digestion (AD) enables recycling of N (and other nutrients) captured in the digestate back to cropping land to meet N requirements in place of synthetic fertilisers. The proposed system will require a combination of established and novel bioenergy crops as feedstock for AD to achieve high and reliable energy yields per ha under NZ conditions. Promising cultivars were trialled at two North Island sites during the 2009-10 season. The following crops were grown: forage sorghum (*Sorghum bicolor*), forage maize (*Zea mays*), pearl millet (*Pennisetum glaucum*), sunflower (*Helianthus annum*) and Jerusalem artichoke (JA, *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 t DM ha^{-1}) was demonstrated by two maize cultivars, two sorghum cultivars and one millet cultivar at a well-watered site. The early drought impact at the second site in 2009-10 was least pronounced on two forage sorghum cultivars (18 and 21 t DM ha^{-1}), while other crops proved less drought tolerant. 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. Biogas yield was projected using the values from the European EU-AGRO-BIOGAS project database. Two crop species were deemed most suitable to further test the CLN concept in 2010-11: two sorghum cultivars that were very high yielding and drought tolerant and JA, an easy-to-establish resource-efficient perennial.

Additional keywords: nitrogen recycling, closed-loop nitrogen, sustainability, land use capability, forage sorghum, forage maize, pearl millet, Jerusalem artichoke, topinambur

Introduction

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).

Conversion technologies used to produce transport fuels from biomass include combustion, anaerobic digestion (AD) and thermochemical methods (Hall and Gifford, 2007). Anaerobic digestion is the most suitable 'rural-scale' technology (Murphy *et al*., 2011) 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 (km) than conversion to biodiesel (see Figure 12 cited in Börjesson *et al*., 2010; BANZ, 2011b) and therefore,
(4) replacing fossil fuels with purified biogas for transport is a highly effective greenhouse gas (GHG) mitigation strategy.

A second opportunity to reduce agricultural greenhouse gas (GHG) emissions is by reducing nitrogen (N) fertiliser, produced from fossil gas. World fertiliser production consumes over 1% of the worlds energy and produces 1.2% of the worlds GHG emissions (Wood and Cowie, 2004). When AD is used, mineral nutrients and undigested carbon compounds can be reapplied (recycled) back to the land on which the crops were produced, thereby largely eliminating the need for external nutrient inputs (Birkmose, 2007; Lukehurst *et al.*, 2010). 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 this energy cropping system is referred to as a Closed-Loop N system (CLN) (Renquist *et al.*, 2010a; Renquist *et al.*, 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, thereby off-setting further GHG emissions and reducing the footprint of the food production.

Modern AD plants can be scaled to fit farms, cooperatives or whole rural districts. Biogas can be used directly for heating or to generate electricity. The highest value use for biogas is as compressed bio-methane (CBG) to fuel vehicles. Modifications to enable a wide range of vehicles to run on CBG are becoming available (AGCO, 2010; Transpacific, 2010). Purified biogas can also be injected into the national gas grid. A feasibility analysis of biogas production on a large farm in Germany has been applied to the NZ situation (Renquist and Thiele, 2008). The feasibility of replacing primary sector fossil fuel use with biogas ultimately depends on economics. Economic drivers that will determine biogas use include international prices for fossil fuels, the economic cost of off-setting greenhouse gas emissions and government incentives addressing national energy security, rural development and land management. Such drivers have led to some EU countries to advance the use of biomass crops and develop AD facilities. Most of Germany's 5905 biogas plants (Biogas Segment Statistics, 2010) have been built in the last decade; these are primarily located on farms, and digest energy crop and manure feedstocks (Anon., 2011).

The biogas yield per ha for energy crop 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*., 2007; BOKU, 2010) for projecting biogas yields from various feedstocks, 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 feedstocks for AD plants (Amon *et al*., 2007; BOKU, 2010). Sunflower and its perennial relative Jerusalem artichoke (JA) are being investigated for use in areas with shorter growing seasons or greater risk of frost. All of these crops have the potential to be dual-purpose.

Global food security (of staple crops) is a critical issue that should influence policies on biofuel production. The fuel technology and associated cropping system needs to make highly efficient use of crop land, or better yet, involve land that would not otherwise be used to produce food crops. This is less of an issue in New Zealand, which does not export grains and other staples that feed developing countries. Furthermore, there is a considerable area of marginal and underutilised land available. Biomass crops in the proposed cropping system would be grown on marginal land that is not usually used for producing arable crops, so as not to compete directly with crop-based food production systems.

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).

The New Zealand arable sector has not felt the same pressure as exporters of horticultural products to make their cropping production system 'green'. Since arable growers primarily supply forage to the dairy/meat sectors, they may find that demand could develop both for forage with a smaller footprint (produced using biofuel) or for biofuel for use by other farms and the wider rural sector.

This paper describes the results of two crop screening studies conducted on marginal land aimed at identifying the most promising purpose-grown herbaceous crops for producing biogas transport fuel using AD.

Materials and Methods

Experimental sites

Two sites were chosen to run the main trials, Kerikeri (Plant & Food Research Centre at 35°11'S; 173°56'E) and Flaxmere (a commercial livestock/cropping farm in the Hastings district at 39°38'S; 176°47'E). Since the perennial JA could not be planted at Flaxmere, yield was measured at the Plant & Food Research centre in Hastings (at 39°36'S; 176°54'E) along with maize cultivar 33M54. Site and soil characteristics are described in Table 1. 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 available waterholding capacity (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.

Nine crops were trialled (Table 2) in a randomised complete block design with three replicates. Plots were 10m 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. Blocks of JA and maize were grown at Hastings, each 15 m long by 5.25 m wide. Three quadrats were harvested from each, to gauge relative DM yield. 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 (43°34'S; 172°43'E). In 2008 tubers were planted in rows 75 cm apart. 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 2.

Table 1: 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	Mangatereteresilty 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

Table 2: 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		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

Cultural operations

Seedbeds at all sites were prepared using full inversion tillage techniques 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 1) with nitrogen supplied at 200 kg N ha^{-1} (urea) at both sites and with 130 kg P ha^{-1} (super-phosphate) applied at

Kerikeri only. The Hastings site had no fertiliser applied to help restrict the growth of the crops on this potentially higher yielding site. 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 (to restrict yield).

Measurements

Field

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.

Biomass composition & methane-yielding potential

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 Massey University Nutrition Laboratory, Palmerston North. These data were then used to calculate the theoretical maximum amount of methane that could be produced by converting biomass to biogas based on the method of Buswell and Müller (1952). The actual yield of methane that these crops would produce if digested was then estimated by comparing the analytical results from this study with those from a large database developed by the EU-AGRO-BIOGAS Forum (BOKU, 2010). This database 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 % 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).

Crops from the present study had a similar chemical composition to those grown in Europe of a similar maturity (as assessed by %DM), therefore the %CE for the New Zealand crops was calculated as the mean of the 10 records closest in %DM to each sample. The maximum (Buswell) yield (Buswell and Müller, 1952) was multiplied by the %CE to estimate actual methane yield on a tissue basis. The inorganic fraction of the DM or total solids is not digestible and is measured as the ash content. The remaining part is termed the volatile solids (VS, equals ash free dry weight) and the specific methane yield is generally expressed on that basis (l CH_4 kg^{-1}

VS). To express the methane yield per ha, the specific methane yield (l CH_4 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 the Discussion.

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. Future experiments designed to test the CLN concept with JA and sorghum will use direct measurement of methane yield in the BOKU laboratory.

Data analysis

Data was analysed in Genstat V9 using the general ANOVA procedure with probability levels set at P=0.05. Means are separated using the least significant difference (LSD).

Results

Above-ground biomass

The forage sorghum cultivar Jumbo gave significantly higher DM yield at the water-stressed Flaxmere site (Table 3) than all other crops except the other sorghum cultivar Sugargraze. Sugargraze yielded higher than 38H20, Bettagraze, Hysun 38 and Speedfeed but not 33M54 or Nutrifeed, which were similar to these other lower-yielding crops.

Dry matter yields were much higher at the irrigated Kerikeri site than they were at the rainfed Hastings site. At Kerikeri, pearl millet (Nutrifeed) and both maize cultivars (33M54 and 38H20) performed much better than they did at the drier Hastings site, yielding equally as high as Jumbo and Sugargraze (both sorghum). Speedfeed and Bettagraze were the two lowest yielding sorghum cultivars at Kerikeri, which were trailed by JA and sunflower (Hysun38). Note that most of the sunflower seeds at Kerikeri had been lost due to bird damage. Seeds generally comprise about 25% of DM (Massignam *et al*., 2009) in an undamaged crop, therefore the 10.4 t DM ha^{-1} yield recorded at Kerikeri may have been closer to 14 t DM ha^{-1}.

The 2009-10 JA data were from three locations, however it was not replicated in Hastings and in Redcliffs. In Hastings the shoots in a single large plot with no irrigation or fertiliser yielded 15.1 t DM ha^{-1}. In replicated plots at Kerikeri the shoot yield was 15.3 t DM ha^{-1}. The LSD value of 6.1 (Table 3) indicates that the latter was significantly less than that of all the C4 grasses. Shoot DM in the second year planting in Redcliffs was higher than either North Island site, with a mean of 17.6 t DM ha^{-1}.

Feedstock composition and methane-yielding potential

Biomass composition of the main four species (with cultivar results pooled) is shown in Table 4. The largest species difference was that sunflower had higher % fat and crude protein than other species. Table 5 presents the methane yield calculations that are derived in part from the composition data shown in Table 4 (refer to Materials and Methods section for the steps in the calculation). Relating the biomethane yields to other fuels in terms of energy is discussed below.

Table 3: 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	21	-	-
$LSD_{(0.05)}$		6.1	3	5.3	8.2
F(Pr)		<0.001	<0.001	0.005	<0.001

Table 4: 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

Table 5: Methane yield parameters for the biomass feedstock crops. Yield potential was calculated from Buswell and Müller (1952); Convertible Energy from BOKU (2010).

Crop	Site	Max yield potential ($l\ CH_4\ kg^{-1}$ VS)	Convertible Energy (%)	Specific yield ($l\ CH_4\ kg^{-1}$ 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

Discussion

Above-ground biomass

Sunflower yielded poorly at both sites (Table 3), either due to drought sensitivity (Flaxmere) or loss of seeds 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 3). 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. In choosing the best-adapted annual species from among the screening trials to carry forward into the 2010-11 field trial for the 'proof of the CLN concept' sorghum appeared better than the maize cultivars.

Sorghum is generally perceived to be a high N-requiring crop. The Kerikeri sorghum averaged 0.68% N and removed 204 kg N ha^{-1}. The available soil N from the previous pasture crop was 126 kg available N ha^{-1}. The 200 kg N ha^{-1} in the fertiliser should be theoretically sufficient without soil N depletion.

Jerusalem artichoke may be preferable to sunflower as a purpose-grown AD feedstock. As 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). However, it probably 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 trial in the 2009-10 season. This was not a problem at the Hastings site.

Feedstock composition and methane-yielding potential

At this stage of the research the methane yield was estimated from biomass composition inputs into the Buswell equation (Buswell and Müller, 1952) and by comparing the composition (Table 4) with similar analyses from the EU-AGRO-BIOGAS Forum database report (BOKU, 2010). The composition of New Zealand maize and sorghum was similar to the European data, except that the New Zealand samples had lower starch but higher sugar content. The effect on methane production should be minimal since both sugar and starch will be fully converted to methane by AD microbes. The Buswell calculation (Buswell and Müller, 1952) result for sunflower was lower than the other species (Table 5). While a recent paper did report higher specific methane yield for sunflower than maize and sorghum (Mursec *et al*., 2009), all those values were much lower than the 300-390 l CH_4 kg^{-1} VS typically reported for those C4 grass species (BOKU, 2010). To explain the low potential yield in terms of composition it appears that the higher oil content in sunflower did not fully compensate for its low cellulose/hemicellulose content. However, another apparent contributor to low specific methane yield in this sample from the Flaxmere trial may have been water stress, which could have lowered the seed weight and oil content. This is supported by the fact that several sunflower samples in the EU database had about double the content of crude lipid as in the local sample.

Since the %CE (Table 5) was estimated to be quite similar in these species the ranking of specific methane yield did not change compared with the potential methane yield. The calculated specific methane yields for maize and sorghum are low to mid-range among reported values (BOKU, 2010) so it will be of interest to see if the direct gas measurements from the 2011 New Zealand samples (currently under analysis) are higher.

Since the DM yields measured in Kerikeri are large, this site has high calculated methane yields per unit area. The lower methane yield per unit area in Flaxmere is a direct result of low DM yield, not biomass composition. The Kerikeri trial results support the capability for such sites in New Zealand to have high DM yields in years with adequate rainfall, which would enable high methane production per ha. However, sorghum is only climatically adapted to the northern half of the North Island (Renquist and Shaw, 2009).

While there is not much current research on JA, there has been considerable past research on breeding cultivars, the biology of the plant and composition of both tubers and shoots (Kays and Nottingham, 2008). The composition of the New Zealand JA sample in Table 4 is quite similar to data from Sweden (Malmberg and Theander, 1986; Gunnarson *et al*., 1985) and North America (Rawate and Hill, 1985). It is therefore also likely that specific biogas and methane yield from AD with JA shoots in New Zealand will also be similar at a given stage of maturity to yields in past findings. Reported yields from ensiled JA shoots averaged 280 l CH_4 kg^{-1} VS (Zubr, 1985; Zubr, 1988; Gunnarson *et al.*, 1985; Mathisen and Thyselius, 1985). This puts the specific methane yield for JA in the same range as sorghum. Verification that JA will be similar in New Zealand awaits digestion in the laboratory at BOKU (Amon *et al*., 2007) of the ensiled samples from the 2010-11 CLN trial.

To put the CLN biomass production system into practice in New Zealand will require research to quantify the methane energy value in the feedstocks going into the digesters. A laboratory facility such as at BOKU could be set up for direct methane measurement. Ultimately it will be necessary to calibrate a model that uses cost effective composition analysis from such measurement technologies as NIR for calculating methane production commercially in New Zealand. That is why it is vital that this research is done in collaboration with the developers of such a model at BOKU.

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. 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 these trials (West and Marland, 2002). The larger gain would come from replacing rural petroleum fuels. To quantify this 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 biomethane 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, pers. comm., 2008). In addition it required another 25% of the gross energy return to operate the digester and purify the biogas into compressed biomethane (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.

To quantify the environmental benefits of fossil fuel replacement within the CLN system the energy input requirements (just determined for the CLN system as the boundary) are subtracted from the gross energy produced in the methane. The gross yields from the data in Table 5 for maize and sorghum (roughly 8000 m^3 CH_4 ha^{-1}) equals about 300 GJ ha^{-1} (NZ Energy Data File, 2011; Materials and Methods). Subtracting 30% for the combined energy input to grow the crops and to produce compressed biomethane (Stewart, 1983) leaves about 210 GJ ha^{-1} as the net fuel energy produced in the 'crops to transport fuel' chain.

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%.

It seems clear 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 in the future. The somewhat higher return on energy invested in the production of petroleum fuels will continue to decline as the non-renewable supply of petroleum dries up.

Conclusions

The two crop species selected from this experiment that are considered worthy of further investigation are sorghum and Jerusalem artichoke; sorghum for northern areas and JA for the rest of the country. The two preferred cultivars of sorghum are Jumbo and Sugargraze. High DM yields of sorghum and maize were achieved on suboptimal arable crop land at the trial sites. These findings should be able to be extended to wider areas of New Zealand by using crop models in the final year of the CLN project. Maize is already sufficiently well researched and would be an excellent biomass source for good North Island arable sites and would also yield well in years with adequate rainfall to supplement marginal sites with low AWC.

The yield of volatile solids from sorghum is high and the calculated specific methane yield is good. If confirmed by direct gas yield measurements in 2011, then this crop would be recommended for biogas production on marginal land with low AWC. The JA species must await direct gas measurements since there is insufficient data in the EU-AGRO-BIOGAS Forum database (BOKU, 2010) to calculate the specific methane yield. However, some literature reports have found it to be as high as sorghum and maize.

Full analysis of the CLN concept will be completed in 2012, but results in this paper are already a good indication that this approach of growing feedstocks to produce compressed biogas transport fuel in rural New Zealand is both technologically possible and environmentally sensible. Further research, development and demonstration work will have to be carried out to enable field scale adoption of CLN biomass to biogas transport fuel schemes. The rural sector will have much to gain from its successful uptake in terms of energy security, environmental benefits and future market development.

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