The potential of anaerobically digested crops to supply New Zealand rural fuel requirements

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Abstract

Increased concern over greenhouse gas (GHG) emissions and a stable source of transport fuel for New Zealand has prompted interest in alternative sources of transport fuel. Approximately 50% of New Zealand's GHG emissions come from the agriculture sector. There is little that can be done in the near future about GHG emissions from livestock, but one area that could be readily improved is the use of fossil fuels in agriculture. This paper reports on the potential for anaerobically digested crops to supply New Zealand's rural fuel requirements. The computer model APSIM was used to simulate biomass production on summer dry arable land in 12 different regions of New Zealand. The crops simulated were sorghum followed by winter wheat for the northern half of the North Island, and lucerne for the remainder of New Zealand. The potential yields generated by APSIM were then reduced by 25% to allow for below optimum crop husbandry. Modelling indicated the biogas potential from only 5% of the summer dry arable land in New Zealand to be approximately 830M m^3 CH_4/year. This gave a net yield of 580M m^3 CH_4/year, once internal energy consumption was subtracted. This amount of energy equates to more than twice the amount of diesel fuel used by the Agriculture Sector in 2010. This level of gas production would be an important new addition to the rural economy.

Additional keywords: Closed-loop nitrogen system, methane, biogas, sustainable production, renewable energy, APSIM

Introduction

Increased concern over greenhouse gas (GHG) emissions and a stable source of transport fuel for New Zealand has prompted interest in alternative sources of transport fuel in New Zealand (BANZ, 2011). Approximately half of New Zealand's GHG emissions come from the agriculture sector (WRI, 2010). There is little that can be done in the near future about GHG emissions from livestock, but one area that could be readily improved is the use of fossil fuels in agriculture (Renquist and Thiele, 2008; Murphy *et al.*, 2009;). Renquist *et al.* (2010a; 2010b) proposed that the fossil fuel used in rural transportation might be replaced with biogas from crops grown on marginal land. Crops for biogas were considered as an alternative to tree biomass since the conversion technology is smaller scale (a better fit to farm districts) and the yields are achieved in a much quicker time than trees. The purpose of this paper is to determine if crops grown on marginal land could be used to produce enough biogas to replace the fossil fuel used in rural transportation. This can be done using a crop simulation model. The economics of the system are addressed in the companion paper Renquist *et al*., (2013).

The simulations focus on a novel cropping system for producing biogas featuring a closed-loop nitrogen (N) recycling system (termed CLN) for use on New Zealand marginal land, as described by Renquist *et al*. (2010a; 2010b; 2013). In brief, the system involves growing crops that produce a large amount of biomass on land that is marginal for high-value food crop production. This biomass is converted to energy in the form of methane (CH_4) via anaerobic digestion. All of the nutrients remain in the digestate, which is then returned to the field, hence the name closed-loop N system. 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. The amount of N fixed by the legume component of an energy cropping system (such as the one being investigated here) is likely to more than compensate for any N losses (unless the area of legume crop was very small), creating a surplus of N in the CLN system that may be used to fertilise land used for food-crop production. This would further off-set the GHG emission footprint of the food production. Therefore, both reduced N fertiliser use and fossil fuel substitution for farm and freight vehicles would contribute to reducing New Zealand's GHG footprint.

Crop species that have been investigated for use in the CLN system include forage sorghum (*Sorghum bicolor* (L.) Moench) and maize (*Zea mays* L.) in combination with a winter crop, Jerusalem artichoke (*Helianthus tuberosus* L.), and crimson clover (*Trifolium incarnatum* L.) (Kerckhoffs *et al*., 2011; 2012). A range of plant species could be suitable depending on the climatic conditions. These crops were grown in New Zealand and the biomethane production potential from these crops measured (Kerckhoffs *et al*., 2012). Simulations were run using sorghum, which is a relatively new crop to New Zealand, plus two well-researched crops, wheat (*Triticum aestivum* L.) and lucerne (*Medicago sativa* L.).

Methodology

Overview

To estimate the potential CH_4 production from marginal land in New Zealand, New Zealand was divided into 12 regions that had similar climate, and then biomass yield was estimated using a crop growth model. Potential biomass production in the regions from Hawke's Bay north was estimated by growing a C_4 crop during the summer and a C_3 crop during the winter, and in southern areas was estimated by growing a C_3 crop. Biomass production was then converted to CH_4 production based on measured CH_4 production from New Zealand-grown crops. Details are provided below.

Land and climate data

For the purposes of this study, marginal arable land was defined as land that experienced more than 50 mm of water stress per year (Renquist *et al.,* 2010a). This land was identified from the Land Environments of New Zealand (LENZ) database (Leathwick *et al.,* 2003). Land with similar climates was grouped together into areas (Table 1) and biomass production for each area was estimated by the crop growth model APSIM 7.3 (McCown *et al.*, 1996). Regions with similar temperature and solar radiation profiles but higher water deficits were simulated by growing the crop on a sandy soil with a low water holding capacity of soil that held 92 mm of plant available water, in contrast to a generic silt loam soil used for most regions, which held 151 mm of plant available water in the top 1m of soil. For environments I3-I6, J2, which had intermediate water holding capacity between environments J1, 3, 4 and B6, B9 but a similar temperate and radiation profile, and sandy soil was assumed and an intermediate yield was estimated for this environment. A sandy loam soil was also used for northern coastal sands.

Weather data were taken from climate stations (NIWA, 2012) in each of the environments described in Table 1, and then crop growth was simulated for 14-31 years depending on the availability of weather data; biomass yield was averaged across the years.

Agricultural Production Systems Simulator (APSIM) modelling

In areas north of Hawke’s Bay biomass production was estimated for a summer sorghum - winter wheat rotation. In areas south of Hawke’s Bay, biomass production was estimated for a crop of lucerne. Both sorghum and lucerne are suitable crops for summer dry areas.

To calibrate the sorghum model in APSIM 7.3 for cooler New Zealand conditions, phenology and yield measurements were collected from the experiments described by Kerckhoffs *et al*. (2011; 2012). The phenology measurements included emergence date, leaf emergence rate and flowering date.

Table 1: Estimated biomass and methane production from arable land in different summer dry regions in New Zealand. Estimated yields are 75% of those modelled by APSIM. Sorghum followed by winter wheat were grown in areas from Hastings northwards, and lucerne to the south. VS = volatile solids.

LENZ environment label	Area descriptor	Representative weather station	Area (ha)	Water deficit (mm/year)	Solar radiation (MJ/m^2)	Annual temp. (°C)	Slope (Degrees)	Estimated yield (t DM/ha)	DM produced (Mt)
A1-3	North Cape	Kaitaia on a sandy soil	82,393	103-121	15.3	15.7-15.8	1.2-5.5	20.0	1.65
A4-A5, G1	Northland and northern coastal sands	Kaitaia on a sandy loam	500,894	51-85	14.9-15.1	14.3-15.3	0.6-2.5	25.3	12.69
B1-B5, B7	Central dry lowlands	Hastings	557,772	62-181	14.3-15.2	10.7-13.3	1.2-9.0	28.0	15.61
B6,B9	Marlborough	Blenheim on sandy soil	48,134	248-261	14.9	12.2-12.4	2.1-3.9	10.0	0.48
C3, F4, I2	Central Wairarapa, Southern Hawke's Bay	Masterton	731,089	93-107	14.0-14.2	12.2-12.7	0.6-7.9	13.2	9.63
I3-I6, J2	Central poorly drained soils, Marlborough well drained soils	Blenheim on sandy loam	188,697	182-225	14.1-14.8	11.3-13.8	0.2-2.9	11.2	2.11
J1, 3,4	Marlborough and lower Nth Island river valleys	Blenheim on a silt loam	180,485	97-130	14.2-15.3	12.0-12.7	0.9-1.8	12.6	2.28
L1, L2,L4	Southern South Island lowlands	Gore on a sandy soil	625,705	54-114	12.4-12.6	9.8-10.5	0.4-2.8	15.8	9.87
N1	Canterbury Plains	Lincoln	404,783	183	14	11.3	0.7	11.8	4.79
N2-N3	Inland Canterbury Plains, South Canterbury, Otago Plains	Timaru	1,092,973	82-113	13.0-13.6	9.5-10.5	0.3-4.2	9.7	10.62
N5-N7	Ranfurly, Wanaka, Upper Waitaki, eastern Central Otago	Lauder	273,650	194-238	13.6-13.8	9.1-9.2	0.2-1.6	5.7	1.57
N8	Alexandra, Cromwell to Luggate	Clyde	39,141	307	13.9	10.2	2.3	4.0	0.16
Total biomass production (Mt DM) from arable land in New Zealand with >50mm annual water stress (marginal land)									71.45
5% of total biomass production (Mt DM)									3.57
Net CH_4 production from 5% of marginal arable land (Mm^3 CH_4) [(MtDM × 89% VS – 10% transport losses) × 290 m^3CH_4/t VS – 30% energy losses]									580

The sorghum model in APSIM (Hammer and Muchow, 1991; Keating *et al.*, 2003) generally predicted the phenology of sorghum quite accurately, but underestimated the yield (see Results and Discussion). Therefore a number of changes were made to the APSIM model. The model that used these changes is hereafter referred to as the 'modified' model. The performance of the modified model is discussed in the Results and Discussion. The changes made to the model were:

(a) Radiation use efficiency was increased from 1.25 to 1.6. The value of 1.25 in the sorghum model was replaced with the same values as used in the maize model (i.e. for stages 1-12 the values used were 0, 0, 1.6, 1.6, 1.6, 1.6, 1.6, 1.4, 1.3, 1.3, 0, 0). This change had the greatest effect on increasing yield.

(b) The light intensity at which the leaves were dying was decreased from 2 MJ/m^2 to 0.5 MJ/m^2. This gave a rate of leaf death that matched better with the rate observed in the field trials.

(c) A small change in the rate at which thermal time was accumulated was also made, to increase the rate of leaf appearance slightly at lower temperatures. The rate at which thermal time accumulated was changed from 0, 19, 0 at cardinal temperatures of 11, 30 and 42°C respectively, to 0, 1, 19, 0 at cardinal temperatures of 10, 11, 30 and 42°C respectively. A similar, although larger change was found to be necessary when adapting a maize model (developed with Australian and USA data) to New Zealand conditions (Wilson *et al.*, 1995).

(d) x_ave_temp was changed from 8 20 35 50 to 8 14 35 50. This change increased yields in the Hastings run by 5 t DM/ha.

Parameters used for the APSIM model are given in Table 2.

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

Table 2: Parameters used to run the APSIM simulations to estimate crop yields in different environments.

	Lucerne	Sorghum	Wheat
Cultivar	Kaituna	Late	Rongotea
Sowing density ($seeds/m^2$)	850	127	250
Sowing date	10 Apr.	15 Nov.	7 Apr.
Harvesting date(s)[1]	20 Feb., 15 May, 15 Nov., 31 Dec.	1 Apr.	8 Nov.
Nitrogen (kg N/ha)	0	150	80

[1]Cut to 40 mm height

Results and Discussion

Estimating sorghum yield

Sorghum phenology predicted by the original APSIM model (Hammer and Muchow 1991; Keating *et al*., 2003) matched well with phenology observed in Kerikeri (Table 3). This is probably because the latitude of Kerikeri is closer to the Australian latitudes where the APSIM model was developed, compared with Hastings, which is further south.

For Hastings the original APSIM model better explained the observed phenology than the modified model, but for Flaxmere the modified model fitted better. The reason for the poorer fit at Flaxmere may have been because there were no weather data for the Flaxmere site so Hastings data was used. Hastings is approximately12 km closer to the coast. It is likely that the Flaxmere site is warmer than the Hastings site, which would have improved the predictions of the phenology by the original model. Therefore, whilst the modified model may have predicted yield better than the original model, it generally did a poorer job of predicting the phenology. The low yields predicted by the original model indicates there is a need for further research before the APSIM model can be used successfully in cooler regions of sorghum production such as New Zealand.

Table 3: Observed and predicted yield parameters for sorghum for the three experimental sites. Predicted yields are from both the original and modified APSIM models (see text for details).

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

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

The potential biomass yields for each region estimated by APSIM are then reduced by 25% to allow for compaction, pests and disease and other limitations (Table 1). It is then assumed that only 5% of the marginal land in each region is planted in a biofuel crop.

The total potential biomass from marginal land is over 71M t DM/year; 5% of this land will therefore yield about 3.6 Mt DM/year (Table 1). A calculation of methane gas yield from this biomass uses the specific methane yield measured for sorghum grown in New Zealand (Kerckhoffs *et al.,* 2012). A conservative factor of 89% has been used to convert total DM to volatile solids, based on the highest ash content of 11% measured during our trials (Kerckhoffs *et al.*, 2012). The tonnage of volatile solids on 5% of the land is therefore 3.2M t volatile solids/year. Assuming a further 10% loss of biomass in the process of transportation, silage making and loading into the digester this becomes 2.9M t volatile solids/year.

The specific methane yield from sorghum is about 330 m^3 CH_4/t volatile solids (Kerckhoffs *et al.,* 2012), 335 m^3 CH_4/t volatile solids for lucerne (Amon *et al*., 2007) but only 250 for winter wheat (Amon *et al*., 2007). Simplifying to a single value of 290 m^3 CH_4/t volatile solids, the resulting production is 830 million m^3 of methane from 5% of marginal arable land base that is prone to being summer dry.

Using conservative numbers, around 30% of the gross biogas energy produced is required to operate the entire biogas crop to fuel system (Stewart, 1983; Börjesson *et al*., 2010). To calculate the total available net energy, this internal energy consumption of 30% was deducted from the gross energy yield of 830M m^3 CH_4/year, resulting in 580M m^3 CH_4/year of available net energy. The conversion to diesel equivalent equals 548M litres (NZ Energy Data File 2011). The 580M m^3 CH_4/year has an energy content of 19.7 PJ, which represents more than twice the diesel fuel used by the Agriculture Sector in 2010 (8.93PJ; NZ Energy Data File, 2011). The associated environmental benefit of this fossil fuel energy substitution is for a reduction in GHG emissions of 1.44M t CO_2, based on a conversion factor of 73.25 kt CO_2 per PJ of diesel combusted (NZ Energy Data File, 2011).

Conclusions

Producing CH_4 fuel from crops offers many benefits to the rural sector. The biogas potential from only 5% of the summer dry arable land in New Zealand is projected to be approximately 830M m^3 CH_4/year gross, with a net yield of 580M m^3 CH_4/year. This represents 1.5 times the amount of diesel fuel used by the Agriculture, Fishing and Forestry Sector in 2010. If this level of gas production can be realised, and the fuel, heat and power put to use in rural New Zealand, the result would be an important new addition to the rural economy.

Additional benefits of developing the use of biogas in rural New Zealand include:

(a) a decreased risk to production in the event of a global fuel crisis
(b) a decreased GHG footprint, which should enhance our clean green image and therefore our marketing credibility internationally
(c) enhanced diversity of markets for crops in New Zealand, which should enhance the stability of rural incomes.

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References

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. 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. *Bioresource Technology* 98:3204.

BANZ. 2011. New Zealand Biogas Strategy. Retrieved on 20 July 2011 from http://www.biogas.org.nz/Publications/Home/BANZ-Biogas-Strategy-20110224.pdf. Biogas Interest Group (BIG), Bioenergy Association of New Zealand. 34 pp.

Börjesson, P., Tufvesson, L. and Lantz, M. 2010. Life cycle assessment of biofuels in Sweden. Report No. 70 - Environmental and Energy Systems Studies. Lund University, Lund. 85 pp.

Hammer, G.L. and Muchow, R.C. 1991. Quantifying climatic risk to sorghum in Australia's semiarid tropics and subtropics: model development and simulation. pp. 205-232. *In*: Climatic risk in crop production: Models and management for the semiarid tropics and subtropics. Eds Muchow, R.C. and Bellamy, J.A. CAB International, Wallingford.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy* 18:267-288.

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.

Kerckhoffs, H., Trolove, S., Heubeck, S., and Renquist R. 2012. Biogas fuel from a closed-loop N supply cropping system. MPI-Information Paper No: 2014/10. Ministry for Primary Industries, Wellington. 84 pp.

Leathwick, J., Morgan, F., Wilson, G., Rutledge, D., McLeod, M. and Johnston, K. 2003. LENZ Technical Guide. Ministry for the Environment, Wellington. 237 pp.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M. 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50: 255-271.

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.

NIWA 2012. The National Climate Database. Retrieved August 2012 from http://cliflo.niwa.co.nz/.

NZ Energy Data File 2011. NZ Ministry of Economic Development. Retrieved on 29 October 2011 from: http//www.med.govt.nz/upload/77238EnergyDataFile_2011.pdf.

Renquist, A.R. and Thiele, J.H. 2008. Potential to produce biogas from maize silage for stationary power and biofuel. Crop & Food Research Confidential Report no. 2167.

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

Renquist, R., Trolove, S., Shaw, S., Heubeck, S. and Kerckhoffs, L.H.J. 2010b. New Zealand: Novel biomass production for sustainable biofuels using new crop cultivars and legumes in a closed-loop nitrogen supply cropping system for use on marginal land. pp. 1483-1492. *In*: Proceedings of the 9th European International Farming Systems Association (IFSA) Symposium, 4-7 July, Vienna, Austria.

Renquist, R., Heubeck, S. Trolove, S. and Kerckhoffs, L.H.J. 2013. An overview of the Closed-Loop Nitrogen System as a means to supply New Zealand rural fuel requirements *Agronomy New Zealand* 43: 107-122.

Stewart, D.J. 1983. Methane from crop-grown biomass. pp. 85-109 *In:* Fuel gas systems. Ed. Wise, D.L. CRC Press, Boca Raton, Florida.

Wilson, D.R., Muchow, R.C. and Murgatroyd, C.J. 1995. Model analysis of temperature and solar radiation limitations to maize potential productivity in a cool climate. *Fields Crops Research* 43: 1-18.

WRI 2010. Climate Analysis Indicators Tool (CIAT Version 7), World Resources Institute, Washington DC.