New Zealand: sustainable biofuel production using new crop cultivars and legumes in a closed-loop nitrogen supply cropping system for use on marginal land

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Abstract: *This paper describes a novel energy crop production system that reduces greenhouse gas (GHG) emissions both by direct fossil fuel substitution and substitution of fossil fuel derived N-fertilizer by virtue of its closed loop nitrogen (CLN) supply feature. The system will be used on New Zealand (NZ) marginal lands, enhancing their productivity with energy crops that will compete little with food crop production. New non-woody plant types with high nitrogen (N)-use efficiency in combination with N-fixing legumes are being trialled for their potential to produce biomass in sustainable rotations not requiring external N. A key element of the CLN system is the conversion of biomass into biogas using anaerobic digestion (AD). Since AD almost completely retains the fertilizer value contained in the feedstock during fuel (biogas) production the additional nitrogen fixed by leguminous crops in the rotation will not only meet the N requirements of the energy crops, but will also provide a surplus that can be used for food crops. This unique feature makes CLN biomass cropping particularly sustainable. Uptake of this new sustainable energy crop production system will increase the value of marginal land and sustain rural and Maori communities in New Zealand with a secure, affordable source of fuel. This will have increased future importance as the frequency of droughts in eastern areas of New Zealand is predicted to increase following climate change. Once the benefits of this integrated cropping and fuel supply system are proven in rural NZ it will have applicability in many countries.*

Keywords: *New Zealand, biofuel, biogas, anaerobic digestion, marginal land, closed-loop nitrogen supply*

Introduction

Reducing greenhouse gas (GHG) emissions from the agricultural sector and making cropping systems more sustainable can be achieved. This paper describes a current research project on bioenergy crops in New Zealand (NZ) called "Novel biomass production for sustainable biofuel using new crop cultivars and legumes in a closed-loop nitrogen supply cropping system for use on marginal land". It is funded through the New Zealand Foundation for Research Science &Technology (FRST) using Sustainable Land Management for Climate Change (SLMACC) funds from the Ministry of Agriculture and Forestry (MAF). This fund is aimed at developing solutions for agricultural GHG mitigation, climate change (CC) adaptation and novel rural business opportunities. The presented project has the potential to advance all three of these goals. The first mitigation opportunity is to reduce greenhouse gas (GHG) emissions from the use of fossil fuels by farm equipment and rural trucking which consume between 10 and 20 PJ of fossil fuel p.a. depending on definition/classification. Substitution with biofuel on this scale, ~ 7% of current New Zealand petroleum fuel use (NZ Ministry of Economic Development, 2009), can hardly be met by wastes/residues alone and requires purpose-grown energy crops, since many waste streams are concentrated around population centres and are therefore better utilised in an urban setting. The research will design a novel energy crop production system that reduces GHG emissions arising from the manufacture of nitrogen (N) fertiliser (a second mitigation effect). This will be achieved by virtue of its 'closed-loop N supply (CLN)' feature. Use of this system on marginal land, where these energy crops will compete little with food crop production, will contribute to MAF's CC policy goals on land management. Adaptation to CC is also served by the proposed new cropping system, both by new findings on use of marginal land and by testing of cultivars with sub-tropical parentage that are adapted to warmer climates and water deficit – which is predicted to increase in eastern areas of New Zealand (Mullen et al., 2005). Plans to develop a biofuel supply via biomass crops often refer to use of marginal land. This will build upon existing classification tools, such as the NZ Land Use Capability (LUC) classes (Lynn et al., 2009). The project will test the closed loop N supply concept (CLN) by quantifying the main elements of such a system and integrating results into a 'virtual CLN' model. The biomass crops include new annual cultivars with high nitrogen (N)-use efficiency in combination with N-fixing legumes. Perennial crops, including legumes, will also be emphasized. The project will also help assess whether sustainable biomass production is possible under New Zealand conditions within rotations on current crop land, which is being researched at BOKU, Austria (Amon et al., 2007).

The key to the CLN system is that the crop biomass is to be converted into biogas using anaerobic digestion (AD), a proven energy technology that is the biomass conversion technology that most directly conserves the mineral macronutrients, nitrogen (N), phosphorus (P) and potassium (K) and other micronutrients in forms readily usable by crops. For that reason, linking biomass cropping to biogas production has the potential to replace all the manufactured N fertiliser (using fossil gas) that these crops would have required. Biogas digesters using high DM crops and legumes as the feedstock, will produce enough digestate to supply the energy crops with supplemental N if needed and there is a real opportunity to supply the surplus N from the digestate to food crops. In addition, the AD technology has a superior fuel energy ratio and lower GHG impact than other biofuels (EC, 2006).

Uptake of this new sustainable energy crop production system would have several added social benefits. New crop production and associated local biofuel infrastructure will create business opportunities: it will create new use for underutilised land and will increase the value of marginal land. In addition, it will facilitate the emergence of self sustaining rural communities and regions with a secure, affordable source of biofuel, while reducing the NZ trade deficit. Several new service businesses would be supported by an emerging new biofuel cropping sector, including feedstock crop breeding by seed companies and transport and processing of both biomass feedstock and biogas digestate by agricultural contractors, possibly utilising biogas-fuelled vehicles. Civil and mechanical engineering as well as consulting jobs would be created for the construction of anaerobic digester plants, biogas upgrading plants and vehicle conversions. Furthermore, high and low skilled jobs for operating these facilities would be created in rural areas that would greatly benefit from additional employment opportunities. Some of the market for biomass growers will be created by AD facilities already planned to be built by intensive livestock operations. These will address environmental problems by converting manure to biogas. Their AD plants will be more cost effective if they include plant biomass, since it yields much more biogas per tonne than the dilute manure slurries typical in NZ livestock farming.

This project will be done in collaboration with the BOKU research team, who will quantify the biogas yield potential from different crop materials (Amon et al., 2007). We are also collaborating with a research project at the "Landwirtschaftliches Technologienzentrum Augustenberg" in Karlsruhe, Germany that has assessed biogas production from over 300 species of sorghum. There will be strong links with existing New Zealand research programmes, including research engaging Māori communities. The outcomes will be a step change in the environmental, economic and social sustainability of biofuel production in New Zealand.

Design of an energy crop production system featuring closed-loop N supply

The closed-loop N supply (CLN) system

Replacing nearly all fossil fuels used in agriculture and most rural trucking will require purpose-grown energy crops since the current available tonnage of surplus crop residues is insufficient. Woody energy crops could be grown on farms, but wood processing technologies to cellulosic ethanol are large scale so could not be located closely enough to New Zealand's widely distributed farms. Growing non-woody biomass crops presents a better prospect for arable and livestock farmers who may have areas of underutilised land. Producing biomass is a proven strength of NZ's primary sector and a good alternative to imported petroleum (coal being constrained by GHG concerns). However, the highest yielding arable crops also tend to have high nutrient requirements, particularly nitrogen (N). Nitrogen fertiliser is synthesised from natural gas, another fossil fuel that causes GHG emissions. The solution lies in a closed-loop N supply production system for energy crops on 'marginal' land that can result in reasonable biomass yields to replace fossil fuels and also mitigate the emissions embodied in N fertiliser production.

The most effective mitigation of emissions from fossil fuel and N fertiliser will be achieved by combining a smart biomass production system with a technology for converting biomass to biofuel that is well integrated with the farming system. This requires the scale of biomass processing to be flexible, to match the needs of individual large farms or collectives of smaller ones. Smaller scale also allows fuel plants to be located near the crops so N removed by the crop can be easily returned to the next crop in the end product after energy is extracted. It also reduces costs associated with transporting the biomass to the fuel conversion plant. A conversion technology with these features is already available – anaerobic digestion (AD), which converts non-woody biomass to biogas. Further, the fuel produced will have a high fuel:energy ratio (FER) and a high sustainable fuel yield per hectare of feedstock. The FER for biogas from maize silage is about three times higher than bioethanol from grain and the energy yield is more than double. The new crop production system should give an even better FER due to lower fertiliser inputs.

The environmental effectiveness of displacing emissions from agricultural fuels and N fertiliser is apparent. These emissions are both significant and easier to mitigate than other farm sector emissions. Environmental sustainability underpins our design aim of using those marginal lands that avoid adverse impacts on biodiversity and forests that already store carbon. The unique feature is that the CLN system uses legumes to add new N to the system each year and captures N in the biogas digester for return of N to the soil to grow a high DM energy crop. Together these will mitigate 100% of N fertiliser use and may create a surplus of N that can be delivered to high N-requiring food/feed crops.

The economic dimensions of GHG mitigation require that technologies have long-term viability and are cost-effective. The proposed biomass production and conversion system has very good potential to deliver both aspects. Undoubtedly its uptake would be accelerated by incentives for building the required biogas plants. Certainty of viability is greater with AD than other conversion technologies based on overseas commercial experience using maize silage. Biofuels are likely to earn carbon credits in the future and the better FER with biomethane than other biofuels should also favour the economics of AD. The International Energy Administration (2008) recently concluded that second generation liquid fuels are still a decade away from making a major impact on GHG emissions.

Identifying the most suitable conversion technology – anaerobic digestion

With the aim to supply nutrients to biomass crops in the most renewable and localised way possible, anaerobic digestion (AD) is clearly the preferred choice among technologies for conversion of biomass to biofuel. AD has already been identified (Amon et al., 2007) as the way to link food and biomass crops and biofuel processing for large synergy/sustainability gains on current crop land in Europe.

To achieve a closed loop nutrient supply, crop N requirements are met by the N contained in the digestate from the previous crop, plus additional N from a legume crop to make up for the small losses in N that occur during digestion and application to the field. Losses of nutrients during digestion is very small (Hartmann, 2006) and losses of N from the digestate applied to the field is small if it is incorporated into the soil at a rate that matches plant demand (Palm, 2008). These small losses could be met by growing a winter legume. This would be more challenging on marginal land than good crop land. However in more challenging environments the CLN system could use perennial crops, with a perennial legume grown beside a perennial energy crop. Depending on the amount of N contained in the legume crop, the N needs of energy crops may not only be fully met, but exceeded.

Identifying suitable land

The New Zealand Land Use Capability (LUC) system

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

Marginal land for arable production has already been defined under the land use capability (LUC) system. Under the LUC system, land that is most suitable for crop production is classified as class 1, land with slight limitations is placed in class 2, land with moderate limitations is in class 3, and land with severe limitations for arable production, but where it is still possible, is classified as class 4 (Lynn et al., 2009). Land that is not suitable for arable production (usually because it is too steep) has a classification number of 5 to 8. The mapping procedure in Figure 1 makes use of the LUC classes for a specific analysis. Moisture stress was estimated based on the Annual Water Deficit layer of the Land Environments of New Zealand dataset (Leathwick et al., 2003). Areas under moisture stress are defined as those places where the accumulated monthly evaporation that exceeds monthly rainfall is above 50 mm over the course of a year. For the purposes of this study, trafficable land that is classified as least suitable for crop production, i.e. classes 3 and 4 are considered as marginal land for crop production.

Figure 1. Arable and marginal land mapped according to susceptibility to moisture stress.

Another potential biofuel is cellulosic ethanol from forest residues or purpose grown short rotation forests. While the technology is further away, it may become a good biofuel source. It does not compete for land with the CLN non-woody crops since there are large areas of steeper land (within LUC classes 5-8). One other advantage of non-woody biomass is that the cost of harvesting forest residues ($44/tDM) is much greater than the cost of harvesting crop residues ($28/tDM) for biofuel production (Hale et al., 2006), and whole crop harvest costs have an even greater cost advantage over forests.

Land classified as classes 3 and 4 still has moderate to severe limitations for crop production and so competes little with food crop production. The Land Use Capability Handbook states that “In general, class 4 land is suitable for only occasional cropping (e.g. once in 5 years or less frequently).” This suggests that the location of annual biomass crops, such as C4 grasses, should be primarily in LUC 3 sites, but that perennial biomass crops may be a good alternative to grazing or hay crops on LUC 4 land, which comprises 10.5% of the land in NZ. Since the biomass crops will often be useable as livestock forage, their use will determined in part by price. Animal feed prices fluctuate greatly depending on the season, being high in drought, whereas under good growing conditions there is little demand for animal feeds. Demand for biomass by biogas digesters will be steadier but could be met in larger part during years of low forage demand, and ensiled where it will keep for several seasons.

The LUC system further divides the land in classes 3 and 4 according into 4 subclasses according to the type of limitation. These are: soil limitations, susceptibility to erosion, wetness, or climatic limitations. For the initial phase of this study we have focussed on land with low water-holding capacity. It is also the land that is easier to harvest than the wet land. Land that is susceptible to erosion would be less suitable to arable crops, but the CLN system proposed here for arable crops could be successfully used with perennial crops. A perennial legume crop could be grown alongside a perennial energy crop, to provide the small amount of top-up N necessary to cover minor N losses during digestion and utilisation by the crop.

Niche areas of land for the CLN system

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

- **Intangible benefits (community or environmental value).** Despite the fact that biofuels may not compete with food crops or animal feeds on a strict $/$ comparison, they may have a high intangible benefit. For example, using tractors powered on biogas may give an organic grower a competitive advantage over one who doesn’t. Biofuels will help a producer become carbon neutral, and a brand that is carbon neutral may be preferred over similar brands that are not. Biofuels may have additional value in ecotourism industry. Therefore, areas with a high number of ecotourism operators, and growers with a strong eco-friendly branding focus may decide to grow crops for biofuels.
- **Remote areas.** If the distance to market is large, then this decreases profits for growers from food crops and animal feeds. However distance is not a big issue for biogas production, since the digesters can be located near or even on the farm. There is not a significant ‘economy of scale’ issue with biogas production, unlike liquid fuel production plants, making biogas an ideal candidate for providing remote communities and regions with a sustainable local source of fuel. An example of this might be remote areas in the East Cape of New Zealand, where liquid fuel prices are high, and there are few markets for high value crops or animal feed (there are few dairy farms in this area – the main market for animal feed).
- **Environmentally sensitive areas.** Regional councils may impose regulations that prevent intensive cropping or dairying in areas where it is desirable to avoid a high N loading, e.g. lakes, rivers or unconfined aquifers. In these situations, a CLN system, which uses plant cultivars that have a deep root system and the capacity to take up a lot of N, may be desirable. Also, the form of N used in the closed loop system is digestate, which is a mixture of immediately available N (ammonium) and slowly available N (organic N) as opposed to most chemical fertilisers, which are all immediately available N. An example of such a situation would be in the Lake Taupo catchment, where Environment Waikato as the local authority is trying to minimize the amount of N getting into the lake ecosystem and therefore dairy farming and the use of N fertiliser is discouraged.
- **Areas with problem weeds.** Land may also become marginal if it is infected with weeds that make it unsuitable for animal feed. For example, alligator weed (*Alternanthera philoxeroides*) is a problem weed in Northland (Northland Regional Council, 2009) and is resistant to

selective herbicides. It is toxic to stock which means that a contaminated crop or pasture should not be made into silage. However, the presence of alligator weed in a biofuel crop would not cause a problem for biogas production.

- **Short duration crops** Farmers may well have a few months in between important cash crops which would be suitable for growing a biogas crop. Biogas crops are ideal for such situations because they simply need to produce cellulose, they do not need to produce grain, flowers or fruits like many other crops. Break crops are also suitable for use as animal feeds, but there are situations where the crop may not want to be used for animal feed, e.g. the field may not be fenced for stock, the farmer may not have a water supply for stock, there may not be many grazing animals available in the district, it may not be possible to make the biomass into silage if it is during the winter (too wet), etc.

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

Potential for increased suitable area

Land classes 3 and 4 comprise 20% of the land area of New Zealand (Lynn et al., 2009). The bulk of the land is concentrated around Taranaki, Canterbury Plains and Southland regions. There are smaller areas in the Manawatu, Southern Hawke's Bay, inland Wairarapa the Waikato and Central Otago, and then scattered patches throughout New Zealand (Lynn et al., 2009). One reason to focus on C4 plants such as maize and sorghum, is because temperatures are predicted to be higher (Mullen et al., 2008), meaning that the area that is suitable for these highly productive species will increase. Not only are temperatures expected to rise, the potential evapotranspiration deficit is also predicted to increase in the eastern areas of New Zealand in the future (Mullen et al., 2005), therefore water-efficiency is an important trait to focus on.

Identifying suitable biofuel crops

There is a wide variety of crops that would be suitable for the CLN system. Desirable characteristics of a biofuel crop are:

- produces a large amount of biomass with minimal nutrient requirements
- capable of large yield responses to the addition of digestate
- high biogas yield per kg dry matter (DM)
- easy to manage (minimal pest control requirements)
- easy to harvest
- crop can be stored or ensiled
- easy to establish (which is more important on marginal land where crop establishment is much more difficult than on non-marginal land. For this reason perennial crops may be preferred to annual crops)
- suited to the particular kinds of limitations found at the site (For the purposes of this project, we chose to focus on crops that were suited to land prone to moisture stress)
- crops can be established by minimum- or no-tillage techniques. This greatly decreases the loss of soil carbon, compared with conventional conservation, and also decreases the risk of soil loss due to wind and soil erosion, which is more of a problem on marginal land.

Selection of crops for the initial screening trial

There are a large number of suitable crops that we already have considerable experience in growing in New Zealand, therefore it was considered of little value to include these in the screening trial. These included grasses – perennial and Italian ryegrass (*Lolium perenne* and (*L. multiflorum*), tall fescue (*Festuca arundinacea*), cocksfoot (*Dactylis glomerata*), triticale (*Triticum durum x Secale* *cereale*); winter leafy brassicas, e.g canola (*Brassica napus*); bulb crops – turnips (*B. rapa*), swedes (*B. napobrassica*), fodder beets (*Beta vulgaris*); and legumes – tic beans *Vicia faba*), lucerne (*Medicago sativa*), and red clover (*Trifolium pratense*). Bulb crops can produce a large amount of DM, but were generally thought to be less suitable for the CLN system. This is because they have low DM%, reducing transport efficiency and because harvesting the tubers requires much more energy and greatly increases the loss of soil carbon, and the risks of soil erosion and nitrate leaching. They are also more difficult to store than crops that can be ensiled, although for the short term (2 – 4 months) bulbs are easy to store because they can simply be stockpiled beside the digester, provided that the leaves have been removed. If there was a market for the bulbs, such as sugar processing, in New Zealand then use of the tops for biogas would be more feasible.

Therefore the crops chosen were relatively new crop species/cultivars to New Zealand that were potentially suitable for the CLN system (Table 1). Annual crops have the potential advantage of allowing a winter legume to be grown. Two **maize hybrids** were selected, one long maturing cv with subtropical parentage and one short season cv. Both have been successful high biogas yielding cultivars, but by different mechanisms. Maize produces the most biomass of any annual crop. The main need is to make it more N-use efficient. It may be plausible to do this by increasing the planting density of maize to encourage more stem production and less leaf. Increased stem production would lower the N requirements of the crop, making it more favourable for our closed loop N system. However, increasing the planting density is also likely to increase early water demand of the crop, with negligible increase in final crop yield.

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

Forage **sunflowers** have been included in the screening study because of their low nutrient requirements and suitability to a wide range of environments. It is likely that their biomass yields will be lower than C4 annual grass crops, but there is little data on forage sunflower biomass production in New Zealand. Therefore it was decided to include them in the study. **Hemp** has high yield potential under moist conditions, but because of the regulatory issues around commercial growing approved cannabis cultivars, it was decided that this plant was not an option for New Zealand, at least in the short term. High DM cultivars of hemp are also likely to be adversely affected by dry summer conditions, which is a problem for large areas of marginal land. **Crimson clover** is a relatively untested legume in New Zealand. The reason why it has not been grown to date is that legumes are predominantly used for animal feed, and crimson clover is hairy and relatively intolerant of hard grazing. However crimson clover should grow well under New Zealand conditions and produce a large amount of high quality biomass over autumn – spring. Crimson clover plots were included in the trial and sown in March.

Topinambur or Jerusalem artichoke is also a new crop to New Zealand. Being a perennial it has advantages of less cultivation requirements, which reduces the risk of soil erosion and nutrient leaching. Since topinambur is established from tubers, this reduces the risk of crop loss at establishment and reduces the need for weed control. However the tubers may also mean that topinambur has the potential to become a weed, which is an important fact to consider in this study. Yields of topinambur stems and leaves (the part used for AD) are lower than many other crops under ideal conditions, but may well yield well under marginal conditions due to its low nutrient requirements and energy stored in the tubers. It was decided that the tubers would not be harvested due to the greatly enhanced risk of soil erosion, nitrate leaching, greatly increased energy cost of harvesting the biomass and loss of soil carbon. However, the tubers could be harvested at the end of the cropping rotation when the field needed to be cultivated to establish the next crop. Removing the tubers and spraying re-growth would also greatly reduce the risk of topinamber becoming a weed.

Miscanthus (the sterile triploid *Miscanthus x giganteus*) appears to be ideal for the closed loop N system. It produces a large amount of biomass (5 – 44tDM/ha, Saggar et al., 2007), has low nutrient requirements (Christian et al., 2008), and requires only one cut per year. It also has the advantage of being a perennial, which minimises establishment costs, and the risk of erosion. However, miscanthus biomass is too lignified for AD unless it is harvested earlier than for use in combustion (Heaton et al., 2008). This may risk weakening the rhizome storage of DM and could put the soils at risk of nutrient leaching and erosion (if the biomass is moved off short). Miscanthus is not yet freely available in New Zealand and so was not included in the screening trial, but there are biomass trials being conducted at the moment on this crop in New Zealand. These results will be considered in deciding whether miscanthus would be suitable for our proposed biogas closed loop N system.

Mapping NZ land categories suitable for CLN biomass production

Once the system has been demonstrated to work, maps will be made that indicates areas that are suitable to grow the selected crops. The maps will be based on growth rules similar to those developed by Mills and Reid (Sustainable Land Use Research Initiative or SLURI project, unpublished). These maps will be used to identify areas that are suitable for growing various crops and can be used to identify regions where interested community groups could be approached about building a digester and using biogas. Yield modelling and economic analyses will be done to determine the feasibility of biogas use in the area. The social implications for rural communities in the areas of NZ where it will be possible to meet a large part of local energy needs with biomass will also be discussed.

Conclusions

The desktop study component of the project led us to conclude that there are some very promising species available to match various New Zealand soil and climatic areas. The two trial sites in the North Island, Hawke's Bay (East) and Kerikeri (North), for screening species to use in the next stage of testing the CLN system were well chosen. The Kerikeri site is both warm and irrigated, which was good insurance in a year with the coldest spring month of October in 64 years followed by a bad early summer drought in Hawke's Bay, the other site. That site was very useful for comparing drought tolerance of species/cultivars, with good differences in crop establishment.

Between proposing and implementing this research project our thinking moved from the view that a CLN rotation would consist of a high DM subtropical cultivar of a C4 grass followed by a winter legume to the alternative that it might consist of 2 or 3 perennial crops in proximity to the same biogas digester. A legume would supply biomass with higher N content (and would have its nutritional needs met by digester effluent that was low in N). None of the leading perennial candidate species have as high an N requirement as maize or sorghum, so there could be a significant net surplus of N from digestate. This could be used for those forage crop species that do need the N. This shift in CLN design was made possible by noting the integrating effects of linking crop rotation design to the use of the crop biomass via AD for biogas production.

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Table 1. Summary of the crops included in the screening trial for biogas production and the pros and cons of their use for the closed loop N system.

Name	Pros	Cons
Maize (*Zea mays* late maturing hybrids)	- High yields (20 to 35 t DM/ha) - Good digestibility - Established production systems - No aging or quality issues if harvest is delayed - High DM% in harvested mass – good for long distance carts - Chemical weed control well established - Can be planted at least 4 weeks earlier than sorghum	- Usually planted with intensive ground preparation (but minimum tillage should work as well) - Relatively high fertiliser inputs required - Less drought tolerant than sorghum and millet
Sorghum (*Sorghum bicolor*) (*S.sudanese*) + hybrids	- Lower nutrient requirements than maize drought tolerant once established (>40 cm high) - One and multi cut management - Can be planted after late maturing winter crops - Herbicide weed control possible - Yields of 18 to 23 t DM/ha after *c.*135 days in Germany - biogas quality better than maize - Drought tolerant	- Only for warm regions of NZ - Cannot be planted before November - Variable yields - Potentially lower digestibility - Low DM in harvested biomass (using the maize harvest system), requires wilting - Relatively high nutrient requirements to achieve decent yield.
Pearl millet (*Pennisetum glaucum*)	- Drought tolerant	- Only for warm regions of NZ - Cannot be planted before November Lower yields than sorghum (Seiler 1993)
Forage sunflower (*Helianthus annuus*)	- Can be planted early in spring (young plants can withstand -5°C) - Relatively drought tolerant - Relatively low nutrient requirements - Early harvest allows early establishment of follow-up crop - Ideal for lighter soils - Chemical weed control possible	- Relatively low yield (7 to10 tDM/ha in the UK) (Bunting 1974) - Fluffy biomass difficult to ensile, particularly when too dry - Little experience in growing the crop in NZ - Low DM% - Requires relatively warm climate (>14°C average temp.) - Plant doesn't regrow – one cut only
Topinambur or Jerusalem artichoke (*Helianthus tuberosus*) (Seiler 1993)	- Established crop survives frost below -30°C - Easy to establish from very small root fragments. - Low fertiliser requirements to establish, may increase in later yrs - No chemical weed control required - Establish topinambur once and harvest for 5 to 10 subsequent yrs - Forage yield potential (6 to 20 tDM/ha) ~8000m^3 CH_4/ha/y. - One cut per yr, although multi-cut may provide higher yields and higher feedstock quality under NZ conditions. - Maize silage technology for harvest	- Parts of proposed production system untested - Bio-security issues, may become a weed - Below-ground biomass produced not easily utilised for biogas production - The lignin fraction of the foliage increases rapidly towards winter.