Biomass Gasification Crops for the Climatic Range of New Zealand

Richard Renquist and Huub Kerckhoffs

Abstract Plant biomass can be used for multiple forms of bioenergy and there is a very large potential supply, depending on which global assessment is most accurate with regard to land area that could be available for biomass production. The most suitable plant species must be identified before the potential biomass production in a particular region can be quantified. This in turn depends on the degree of climatic adaptation by those plant species. In the range of climates present in New Zealand biomass crop growth has less restriction due to water deficit or low winter temperature than in most world regions. Biomass production for energy use in New Zealand would be best utilised as transport fuel since 70% of the country's electricity generation is already renewable, but nearly all of its transport fossil fuel is imported. There is a good economic development case for transport biofuel production using waste streams and biomass crops. One promising conversion technology is thermochemical gasification.

This review identified the most suitable crop species and assessed their production potential for use as the feedstock to supply a gasification plant making biofuel, within the climatic range present in New Zealand. Information from published work was used as a basis for selecting appropriate crops in a 2-year selection and evaluation process. Where there were knowledge gaps, the location-specific selections were further evaluated by field measurements, by distinguishing three categories of growth habit (perennials, summer and winter annuals), by identifying a high-yielding benchmark species for each category and by the use of crop models to simulate yields in 'marginal' site conditions. This review demonstrates how these elements constitute a methodological tool to quantify the rapid screening and ranking of species. The data presented have superseded much of the speculative information on suitability of species for the potential development of a biofuel industry.

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1 Introduction

Plant biomass can be used for multiple forms of bioenergy and there is a very large potential supply, e.g., the Billion Ton Study in the USA (U.S. Dept of Energy 2011; Boundy et al. 2010) and in the EU a study by the European Environmental Agency (EEA 2006) that expressed the primary biomass potential in energy units (Joules) and also million tons of oil equivalent per year. Global scale assessments of how much land will be available for biomass production were reviewed in 2005 (Lemus and Lal) and updated in recent years (Beringer et al. 2011). This review is focused on identifying the most suitable crop species and assessing their production potential for use as bioenergy feedstocks within the climatic range present in New Zealand.

The context for bioenergy development in New Zealand is that roughly 70% of the country's electricity generation is already renewable, but nearly all of its transport fuel is imported (NZ Energy Data File 2011). The country faces rising costs and less certain supply of fossil transport fuels. The most compelling use for purpose-grown biomass is therefore its conversion to transport biofuels, as opposed to heat and electrical energy (Hall and Gifford 2007). Furthermore, New Zealand uses very little coal, so replacing transport fossil fuel is also the best way to reduce greenhouse gas emissions, apart from agricultural ruminant methane. The current government is interested in new energy sources that offer economic development opportunities. The government's New Zealand Energy Strategy has, therefore, incorporated components of the New Zealand Bioenergy Strategy (BANZ 2011), a document by the Bioenergy Association of New Zealand that makes the economic development case for the use of bioenergy using waste streams and biomass crops.

Among the 'biomass to biofuel' conversion technologies, thermochemical gasification is one that is developing well (van der Drift et al. 2000; Franco et al. 2009; Pang 2011; Rauch 2011). It differs from the biological process of biogas production by anaerobic digestion and has been used in the past with either coal or wood as its bioresource/feedstock. This review will assess the use of herbaceous plant species for biomass production within the New Zealand climatic range for the specific end use of thermochemical gasification to produce biofuels.

The products of gasification in Fig. 1 (Rauch 2011) are hydrogen and carbon monoxide, created at specific high temperatures in the absence of oxygen and with careful control of feedstock transit time. This gaseous mixture, once known as 'producer gas', is now called syngas or product gas. It can be used as engine fuel in gaseous form or converted to synthetic liquid fuel, either diesel or petrol. The process has been referred to as 'biomass to syngas to liquid fuel' or BTSL (Pang 2011). The syngas is converted to synthetic diesel via the Fischer-Tropsch thermochemical process, which is also being advanced by current research.

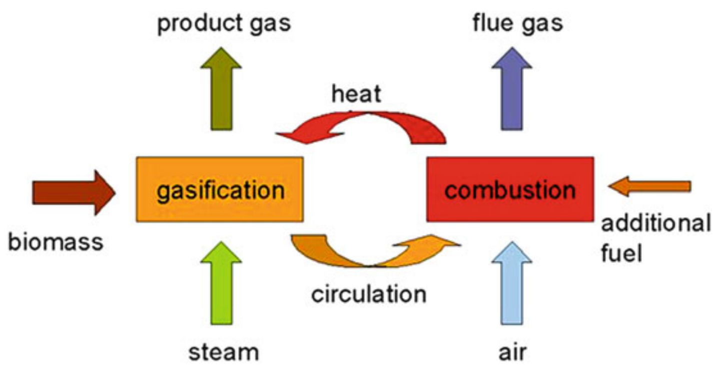

Fig. 1 Working principle of the fast internal circulating fluidized bed (*FICFB*) gasifier with steam as gasification agent, such as used at the Gussing, Austria plant (Figure courtesy of the Vienna University of Technology (www.ficfb.at))

This chapter is primarily a literature review with supporting local assessments to select the best herbaceous crop or weed species, within the context of New Zealand soil types and climatic range that would provided suitable biomass resource for a gasification plant.

The initial literature review was conducted from 2008 to 2010 during which time other activities were also completed to fill the knowledge gaps for species and cultivars not previously tested in New Zealand. We developed estimates of species ranking if grown in 'marginal' sites. This type of land, while lower yielding, is considered more suitable for achieving sustainability objectives.

This paper includes a section that describes the procedure we used to select the best species from the long list of candidates in a time-efficient manner, since highly definitive field trials in the range of climates would require a decade or longer; the section therefore has more aspects of a 'Methods' paper than would usually be found in a review.

This review and screening process has identified a 'short list' of the most promising non-woody species for biomass production and generation of biofuel in New Zealand. The details of their final selection and subsequent field trials will be the subject of a following research paper.

2 Benefits of Biomass for Energy

2.1 Security of Energy Supply

It is a given that an energy supply based on use of non-renewable fossil fuels is not sustainable in the long term. Since this review has a geographical focus, it is relevant that New Zealand imports 97.5% of the oil and petroleum-based liquid fuels it consumes (New Zealand Energy Data File 2011) and therefore also has a security issue related to such delivery. This could arise even before the world petroleum supply is depleted, such that alternative domestic fuel production would be required. Oil is also produced from New Zealand wells, but 95% is bound by export contracts.

2.2 Greenhouse Gas Reduction

Given the strong evidence for anthropogenic contributions to climate change, the displacement of fossil fuels is a technology change that will be beneficial and probably critical to future-proof current and following generations. This is the basis for active bioenergy research programmes internationally. One study considered the aspect of carbon sequestration from growing perennial energy crops in degraded land (Lemus and Lal 2005). The beneficial impact on net greenhouse gas emissions would be from both carbon sequestration and use of the biomass to replace fossil fuels. The latter aspect was also assessed in a 2004 study (Clifton-Brown et al.).

2.3 Energy Crop Research

Energy crops were a topic of considerable interest after the global 1970s oil supply/price crises. Some research continued and it has greatly increased with oil price rises/spikes in recent years. Large research programmes are in progress by the International Energy Agency (Sims et al. 2008) and its Bioenergy division (Bauen et al. 2009; Fritsche et al. 2009; IEA Bioenergy Executive Committee 2009); in Europe (Amon et al. 2007; Ceotto and Di Candilo 2010) and in the USA Biomass Program and biofuel programmes (Perlack et al. 2005; U.S. Dept of Energy 2011; Propheter et al. 2010; Propheter and Staggenborg 2010). Bioenergy programmes are also being set up in the larger developing countries like Brazil (Brito Cruz 2009) and China (Li 2010). Increased research emphasis in the USA is also being placed on breeding of species to enhance their traits as biomass crops (Simmons et al. 2008).

Archontoulis (2011) has noted that most published experimental data from energy crops is quite recent. While species already grown for agricultural uses are well understood in terms of their physiological and agronomic aspects, newer biomass crops especially those that could be classes as ‘weed’ species are less well described.

2.3.1 Agronomic Aspects

Much of the research emphasis on new biomass species has been on agronomic aspects of their production. Several reports, with a focus on dry mass yield, suggest there is a good potential to produce fuels and other types of energy from biomass crops. The range of species being researched in Europe include hemp, kenaf, maize, sorghum (Amaducci et al. 2000; Zegada-Lizarazu et al. 2010) and cardoon (Angelini et al. 2009). Cropping systems research includes energy crops in rotations, some of them dual-purpose species (Zegada-Lizarazu and Monti 2011) and mixed food/energy crop systems that also use food crop residues for energy (Amon et al. 2007; Karpenstein-Machan 2001). Improved tillage practices can have a positive environmental benefit, as will be considered in Sect. 3. Changing from conventional tillage to no-till is shown to enhance C sequestration and decrease CO_2 emissions (West and Marland 2002).

2.3.2 Physiological Aspects

A deeper understanding of new biomass species through physiological research will enhance agronomic practices with these crops. Examples are research characterising the mechanisms of crop response to water and nutrients. Such papers are covered is previous reviews (Bessou et al. 2010) and physiological aspects are reported in several recent research papers on the newer biomass species, for example cynara, kenaf and sunflower (Archontoulis et al. 2011). There are other examples for sunflower (Steer et al. 1993) and sorghum (van Oosterom et al. 2010). Physiological issues such as a crop's impact on the nitrogen cycle are relevant enough to be considered below (Sect. 3.4). Otherwise, since the focus of this review is on species selection for biomass production in New Zealand, physiologically-oriented papers on crop species that have biomass potential will not be reviewed here.

2.3.3 Socio-Economic Aspects

The potential for extensive use of land to produce energy crops raises socio-economic issues to consider. Since a new industry would be established this would require associated infrastructure development and could involve population migration back to rural areas. However, a change of land use from food crops to energy crops is under scrutiny in terms of the socio-economic impacts. A large increase in food prices in 2008 was attributed to use of maize grain and soybeans for fuel in North America. However, a closer analysis showed there were also price impacts from commodity market speculation involved (Mueller et al. 2011). Another study examined socio-economic effects of different facets along biofuel industry development pathways (Duer and Christensen 2010). As with crop physiological aspects, these will not be the reviewed in this paper.

3 Sustainability Issues Using Biomass for Energy

3.1 Land Use Change

Environmental issues with food production (e.g., overuse of fertiliser contributing to nitrate leaching, pesticide use and pesticide residues) have been recognised for many years and are expected to be more challenging as food demand escalates in the coming decades. So, it is not surprising that proposals to use land for the purpose of replacing fossil fuels have raised controversy. The sources of biomass for both food and biofuels need to be produced in a sustainable way, with the net carbon and nitrogen footprints in equilibrium. There is also the moral issue of placing transport biofuel - in part a discretionary consumer product - in competition with food - an essential human need - for use of crop land. For an overview on land use change see Howarth and Bringezu (2009). Direct use of a food species as biomass and use of the best arable land for biofuel in a world that will need to grow more food for a predicted ten billion people by 2050 can be challenged as non-sustainable (Blanco-Canqui and Lal 2009; Davis et al. 2009; Katola and Salmi 2010).

A follow-on issue that has been identified for some cropping situations is **indirect land use change**, since the previous use, eg, tropical rain forest with very high carbon storage, may mean that decades of biofuel production are required before the benefits of replacing fossil fuels will compensate for the carbon debt created by land use change (Ceotto and Di Candilo 2010; Dale et al. 2010; IEA Bioenergy Executive Committee 2009). In Brazil, where biofuel production from sugarcane is often assessed as sustainable, the effects of indirect land use changes were determined by one analysis to exceed the benefits of biofuel substitution (Lapola et al. 2010).

The above efforts to quantify this indirect effect have been useful, but doing so is complex. It has been noted by others that its inclusion in the sustainability standard being applied to biofuels differs from the standard applied to land use change for food production (Kim et al. 2009).

3.2 Land Area Requirements for Biomass Crops

It will be important to predict during the next few decades how much surplus agricultural land could be sustainably diverted to feedstocks for biofuels. Earlier studies of how much land will be available for biomass production were reviewed in 2005 (Lemus and Lal). One later assessment looked in particular at the global amount of abandoned agricultural land available for biomass production (Campbell et al. 2008). Beringer et al. (2011) looked at potential bioenergy production given the environmental constraints and agricultural needs in the context of a global analysis. An assessment of the biofuel production potential using the arable and pastoral lands in Europe was made by Fischer et al. (2010a, b). Another analysis considered the impacts of regional (European Union) policies for biofuel supply on global land use and food production (Banse et al. 2011). A model for southern Australia of the effect of a shift to large-scale biofuel production (Bryan et al. 2010) showed that using food crops like wheat and canola for biofuel was more profitable than their use for food, but the beneficial effects on greenhouse gases and replacing fossil fuels were outweighed by the reduction in food production. There were specific regions within southern Australia where land use for biofuels could be beneficial overall.

The assumptions used in different models result in widely differing calculations of how much land is potentially available for biomass cropping. Bessou et al. (2010) compared the predictions of three global-scale models when the assumed level of agricultural intensification by 2050 was low (organic-type systems), medium and very high. At the low input/intensification level the land required for food would be double the current area, leaving no land for energy crops. For the other two models reviewed the surplus land area available for energy crops at the highest scenario of each is calculated to be 1.3 and 3.6 Gha, respectively (Bessou et al. 2010). These require what may be overly optimistic gains in food crop yields, up to 4.6 times 1998 yields, in order to create 'surplus' land.

3.3 Water Use by Biomass Crops

Water use by biomass crop species needs to be considered at the paddock, the landscape and global scale. At the farm or paddock scale the usual assumption is that biomass crops should be unirrigated. The two bases for this are: (1) the capital cost of irrigation systems is too high for what will need to be a low- to moderate-value crop in order to result in economic energy production, and (2) there are ethical/environmental issues of diverting the water resource from food production or of sourcing it from either surface waters that provide environmental services or non-renewable groundwater resources (De Fraiture and Berndes 2009).

Even for unirrigated biomass production the amount of water transpired is a significant consideration at the global scale. Such an analysis was first done a decade ago (Berndes 2002) which demonstrated the importance of taking the water use into consideration in both the production of energy crops and the industrial processes for conversion to biofuels. With respect to the choice of biomass crops that analysis also presented the wide range in water use efficiency differences between species. Projections of water requirements in 2050 if bioenergy provided 50% of total energy, or biofuel provided 30% of transport, are that the transpiration would be nearly half of that for total food production (De Fraiture and Berndes 2009).

3.4 Nitrogen Cycle and Use by Crops

Nitrogen fertilization is an effective tool for improving the efficiency with which cropland is used. The gain in crop productivity will offset the emission used to produce mineral fertilizers (Ceotto 2005). Unfortunately, nitrogen applied to crops as fertilizers and manure is inefficiently used in most cropping systems. Unused fractions contaminate surface and ground water resources (Pierce and Rice 1988). Losses occur via denitrification, volatilization and leaching (Ceotto and Di Candilo 2010). Galloway et al. (2002) defined reactive nitrogen as all biologically active, photochemically reactive and radiatively-active nitrogen compounds present in the biosphere and atmosphere of earth, and includes inorganic reduced and oxidized forms of nitrogen and organic compounds as urea, amines and amino acids. When it enters agro-ecosystems, reactive nitrogen derived from either synthetic fertilisers or legumes has equally negative environmental impacts.

The reduction of reactive nitrogen in agricultural systems is therefore an important sustainability issue. Growing biomass crops has the potential to reduce the problem. One means to do this is the same as for food crops, i.e. to improve the yield of dedicated energy crops so that production can be achieved on a limited land area. Another strategy is to exploit the potential of dual purpose crops on arable land (Ceotto and Di Candillo 2010). When the crop residues or whole dedicated energy crop in a rotation is converted to bioenergy via e.g., combustion and gasification, the reactive nitrogen is neutralised.

In terms of relative production of damaging reactive nitrogen, crops with a high yield at low nitrogen supply are the lowest producers. Some of the better biomass species have high nitrogen use efficiency, which is a significant environmental advantage resulting in less ground water and runoff pollution derived from nitrogen fertilisers. It also makes them more cost effective.

When legumes are used in a crop rotation, the fixed nitrogen can be taken up and eventually released back in to the atmosphere as benign N_2 if the following crop is used as a bioenergy feedstock for the appropriate conversion technology.

3.5 Life Cycle Assessment

A rigorous assessment of sustainability usually involves a Life Cycle Assessment (LCA) analysis of biofuel production (Börjesson et al. 2010; Katola and Salmi 2010; Davis et al. 2009; Wortmann et al. 2010; Patterson et al. 2008; Blanco-Canqui and Lal 2009). An important aspect of sustainability usually assessed is the relative greenhouse gas production of different fuels. LCA has proven very useful to assess the relative merits of potential future biomass species (Rettenmaier et al. 2010). Some studies have successfully identified biofuels that are relatively poor choices in terms of energy balance and/or environmental impacts (Davis et al. 2009).

The appropriate scope for an LCA is often from ‘cradle to farm gate.’ In one such analysis of perennial biomass crops in Italy (Monti et al. 2009) four biomass species were compared to a food crop rotation in terms of ecological impact on a per hectare basis and on energy impacts. The per-hectare impacts of all four were about half those of the wheat/maize rotation. Three of the four also had much lower impacts than the fourth biomass crop on an energy basis as well, which is clearly essential for an effective energy crop.

3.6 Use of ‘Marginal’ Land for Bioenergy Crops

A species having low input requirements is also likely to be better adapted to utilise ‘marginal’ land. This is not only in the interest of the grower/landowner, creating a new land use for such areas, but is a key aspect of making the biofuel production from biomass sustainable. In order to use performance in 'marginal' land as a species selection criterion, as intended in this review, then 'marginal' itself needs to be reconsidered and better defined. This need has been noted in other analyses of biofuel production (Ceotto and Di Candilo 2010; Robertson et al. 2010; Davis et al. 2009; Dale et al. 2010).

There are several complexities to consider in defining 'marginal' (Dale et al. 2010), but allowing for such considerations, marginal sites can be defined as those which provide on average suboptimal growing conditions for major food or feed crops in the relevant climatic zone. Marginal sites are also defined according to properties of the soil, the topography and the reliability of key weather factors like favourable rainfall and temperature. This is why the term 'marginal site' may be preferable to 'marginal land.'

4 Species Screening, Energy Crop Criteria

Identifying the desirable characteristics of a biofuel crop has been reviewed before (e.g. Ceotto and Di Candilo 2010). We conclude that an ideal New Zealand biofuel crop should possess the following key attributes:

- a species already in New Zealand or having qualities such as sterile seed that enable speedy regulatory approval for importation
- easy to establish, even on 'marginal' land
- can be established by minimum/no-tillage techniques
- early spring growth to compete strongly with weeds
- deep rooting to access subsoil water and preferably a perennial growth habit
- good solar radiation capture and high daily growth rate over a long period
- very high or high dry mass yield
- nutrient and water requirements are low relative to yield
- resilient to the site limitations (e.g., frost or water deficit)
- easy to manage (minimal pest control needs)
- biomass production is above ground
- easy to harvest
- the delivered biomass has a moisture content no higher than that of wood
- has a low nitrogen concentration and low or moderate ash content, and
- can be stored dry or ensiled.

These attributes of an ideal bioenergy crop reveal how to go about improving energy crops in terms of yield and net energy gain (Ceotto and Di Candilo 2010) and feedstock traits such as ash content (Monti et al. 2008), as well as environmental sustainability. Low nitrogen content is both a reflection of lower industrial fertiliser use and lower release of N_2O. Perennial plants usually have better nutrient recycling due to underground storage organs.

This section describes the biomass species we identified as candidates for evaluation. The international literature search results in 2008 came from biomass studies largely aimed at liquid fuels and pyrolysis studies using waste stream biomass, but more recent searches also identified more papers on bioenergy from dedicated crops. Commercial biofuel literature was also a useful source as to which species are attracting interest as biofuel feedstock.

The literature review identified a wide range of potential biomass species. These included crops known to have high dry mass yield in New Zealand arable soils, resident weed species with observed prolific growth, advanced cultivars of arable crop species that could be introduced to New Zealand and overseas biomass crop or weed species with traits such as sterility that would enable introduction to New Zealand.

A compilation of recent New Zealand field data on high biomass arable crops and some weed species, and new dry mass field measurements in commercial crops or small plots were designed to add preliminary New Zealand information on less well-studied species.

This review used additional criteria particular to the research project it was part of, a biomass gasification research project. The net requirement by the operator of a gasifier unit is for feedstocks that collectively can be grown, stored and supplied year-round at a relatively low cost per tonne dry mass.

High dry mass was the best criterion for initial ranking of prospective biomass species. This process was structured by distinguishing three categories of growth habit: summer annual species, perennials and winter annual species, to facilitate direct comparisons of species for which there is only limited information with those that are well-characterised crop species of the same type.

The following subsections provide lists of species (categorised by crop growth habit) and literature review findings for each that provide (1) a brief description of their potential as biomass crops based on yield, (2) relevant aspects of each species' agronomy and (3) whether there are issues making it less favourable to use as a crop in New Zealand.

Some of the species information from New Zealand is specific to geographic regions of the country. Figure 2 can be referred to, noting that low latitudes are in the north end of the country.

4.1 Perennial Species

4.1.1 Lucerne (*Medicago sativa*)

Criteria match for dry mass yield: Lucerne is a widely-grown species in New Zealand, with proven high dry mass yields. Douglas (1986) summarised yield results from 57 different crops/treatments from various authors investigating lucerne growth as far back as 1965, covering all of the major climates and growing environments in which lucerne is grown. Under rain-fed conditions in the South Island highest yields were obtained from lowland soils on alluvium, ca. 15–20 tonnes dry mass per hectare (t DM/ha). In other climates/soil types (e.g. lowland soils on loess and/or fine gravels, hill and upland soils on loess and where rainfall was

Fig. 2 New Zealand map showing regions where the yield of species was assessed. The numbering key for regions discussed in the review is: *1* Northland, *2* Waikato, *3* Hawke's Bay, *4* Canterbury, *5* Southland

350–550 mm/year) lucerne yielded much lower (ca. 8–9 t DM/ha). Crops grown in the North Island under rain fed conditions and on soils derived from recent alluvium were also the highest yielding whilst those grown on soils with volcanic parent material were generally lower yielding (Douglas 1986).

The recent New Zealand research record confirms that lucerne has very high biomass yields, >20 t DM/ha in deep soils in warm parts of the North Island with adequate rainfall (Shaw et al. 2005b). Yields can be equally good in the best South Island soils (Brown et al. 2003). Lucerne is widely adapted to marginal sites with lower water holding capacity as the crop has a strong tap root and is capable of utilising water from deep in the soil profile.

<u>Agronomy:</u> Douglas (1986) also presented data indicating that available water capacity (AWC) has a large, linear effect on lucerne yield with an extra 63 kg DM/ha per mm of AWC. This was particularly true on light stony soils, but the effect is diminished on soils with higher water holding capacity, such as lowland soils on alluvium (Douglas 1986). The recent lucerne research programme by Brown et al. (2000, 2003, 2005a, b, 2006) and Teixeira et al. (2007a, b, c, 2008) were on a deep, high water holding soil. One study by Brown (2003) reported yields of 21.3 in year 1, declining after year 3–17.5 t DM/ha in year 5. Shaw et al. (2005b) reported on non-irrigated North Island lucerne trials in the Hawke's Bay and Waikato regions. On deep high water-holding soil in Hawke's Bay the yield was 9.4 t DM/ha in year

Fig. 3 Lucerne (*Medicago sativa*). When comparing dry mass yield to other biomass species that are only harvested once per year it should be noted that more harvesting effort is required for lucerne, with three or four harvests per year

1 and 22.0 t/ha the next 2 years. The Waikato crop was grown on a hill soil with only moderate water holding capacity (marginal in that respect). This crop yielded 5.4 t/ha in the year it was sown, 17.4 t/ha in year 2 and 14.6 t/ha in year 3.

Lucerne can be considered sufficiently well researched to use in the engineering model for supplying biomass to a gasification biofuel plant and also to use as a species with documented New Zealand biomass production for comparing to yields of less familiar species.

Issues: Lucerne usually has high value as livestock forage, so it may be more expensive for the biofuel plant to purchase than other biomass species. Multiple harvests are also a cost factor (Fig. 3).

4.1.2 Giant Miscanthus (*Miscanthus x giganteus*)(Mxg)

Criteria match for dry mass yield: reported dry mass yields have been high to very high in Europe. The most promising genotype is *Miscanthus x giganteus* (or Mxg). Peak yields are achieved as early as the third year (Lewandowski et al. 2000; Clifton-Brown et al. 2004) or not until the sixth year (Christian et al. 2008) and are higher in warmer climates. Mediterranean research has compared several energy crop candidate species and found Mxg to be a consistent high performer with irrigation or summer rainfall: 27 t DM/ha in Italy (Cosentino et al. 2007) and 28–38 t DM/ha in Greece (Danalatos et al. 2007). Since Mxg was only recently introduced to New Zealand (Brown 2009) the best guide to its yield potential is from an analysis using a UK crop model, which simulated a 13 year mean yield for a site in New Zealand (2008 report by A. Hastings, commissioned by Peter Brown). The peak DM in early winter averaged 27 t DM/ha, while late winter mean DM (the time of harvest) was

18.7 tDM/ha. The mean yields included 6 years with some yield reduction predicted due to water deficit. Details are provided in Sect. 7.2.3.

Agronomy: European research has compared several genotypes (Clifton-Brown et al. 2001). Findings from several UK trials led to release of a Production Guide (DEFRA 2001). Mediterranean research has compared several energy crop candidate species and found Mxg to be a consistent high performer, but Mxg does require irrigation or summer rainfall in Italy (Cosentino et al. 2007) and Greece (Danalatos et al. 2007). Research on harvest timing has indicated that while peak dry mass is in early winter the better time to harvest is after several tonnes of dry mass has been translocated to the rhizome system, along with nutrients to supply early spring growth. The yield at that time is usually 5–10 tDM/ha below the peak (Clifton-Brown et al. 2004).

Physiology: Agronomic and environmental research with Miscanthus led to publication of a growth model, MISCANFOR, in the UK (Hastings et al. 2009). Other studies have quantified response to irrigation and nitrogen (Cosentino et al. 2007). Miscanthus has a low nitrogen content, which is environmentally advantageous because it requires less nitrogen fertiliser to grow and because combustion of the biomass produces less reactive nitrogen than burning fossil fuels or other crop species that are higher in nitrogen content (Ceotto and Di Candilo 2010), and environmental benefits of Miscanthus were greater than other biomass crops (Lewandowski and Schmidt 2006). There is also a positive impact on greenhouse gas emissions by replacing fossil fuels (Clifton-Brown et al. 2004).

Issues:The high cost of establishment is due to vegetative propagation of the sterile triploid Mxg and the need for modified planting equipment. For high dry mass yield Miscanthus requires rain or soil water into the summer, which is often lacking in the Mediterranean climate. While this would not be an issue in most regions of New Zealand with more than 700 mm rainfall, the marginal sites preferred for biomass crops will sometimes be defined by a combination of shallow soil and low summer rainfall. Since New Zealand has a milder winter climate than the European locations, where it has had the most testing as a biomass crop, there may be challenges with winter weed control and early re-growth from the top of the plant before harvest is complete. None of these issues appear to negate the potential of this species in many parts of New Zealand, but they will need to be researched (Fig. 4).

4.1.3 Jerusalem Artichoke (*Helianthus tuberosus*)

Criteria match for dry mass yield: While usually considered a tuber crop, the use of Jerusalem artichoke shoot biomass has been quantified and investigated for producing biogas or forage (Gunnarson et al. 1985; Wunsche 1985; Seiler 1993). The 1980s Scandanavian research documented yields from 7 to 20 tDM/ha (Gunnarson et al. 1985; Wunsche 1985). A trial with multiple shoot harvests in Minnesota (45° latitude) indicated a theoretical yield higher than 25 tDM/ha (Rawate and Hill 1985). The first New Zealand trials had shoot biomass yields in the

Fig. 4 Giant Miscanthus (*Miscanthus x giganteus*). Transplanted as small plantlets with two or more rhizome branches (**a**); height after 12 months, from mid-summer to mid-summer (**b**)

range of 13–16 tDM/ha (Kerckhoffs et al. 2011; see Table 4 in Sect. 6.2.2). Much higher shoot yields (>30 tDM/ha) have been observed in 2011–2012 trials in Hawke's Bay (unpublished).

The highest tuber yield to date (15.0 tDM/ha or 58 tFM/ha) was in Northland, from plants with both shoots and tubers harvested in the winter (Kerckhoffs et al. 2011). However, the Northland tubers had inadequate vernalisation for new spring growth (see the Physiology section).

Agronomy: As a new commercial species in New Zealand, Jerusalem artichoke is a good example of a species needing to have its growth and environmental responses characterised thoroughly. This can be guided by extensive findings in the Northern Hemisphere, although the emphasis there has been on tuber production using annual row cropping methods. If biomass is also produced in that way they the optimal seed spacing needs to be defined. In a perennial system, with some or all tubers left in the ground after the previous season, the growth habit is much different. We observed more than 100 stems/m^2 compared to 10–20 stems/m^2 in the first year. This may require different canopy management if stem population proves to be excessive for optimal use of sunlight.

Physiology: Plant development, such as biomass and nutrient allocation patterns has been investigated in North America. Shoot growth reached peak dry mass 18 weeks after planting in two trials (McLaurin et al. 1999; Swanton and Cavers 1989). However, the highest observed shoot dry mass yields (Wunsche 1985) and our unpublished 2012 results are from long-season crops. Daylength effects, particularly on early tuber-forming cultivars, appear to favour high latitudes (Wunsche 1985) over lower latitudes (Seiler 1993) for shoot dry mass production. However, cultivars vary widely in growth habit and yield, so comparing trial results with different cultivars is difficult.

New Zealand spans a wide range of latitudes, so this mass partitioning effect needs to be evaluated further for the New Zealand cultivar 'Inulinz'. Another matter to clarify is whether shoot growth peaks too soon to intercept full summer radiation. If true then one option is to harvest shoots early for dry mass, then allow the crop to regrow a full-season crop of shoots and sufficient tubers produced for a crop the following year (Rawate and Hill 1985).

Issues: The vernalisation requirement of Jerusalem artichoke tuber buds is well known (Kays and Nottingham 2008). In 2010, this was not met in northern New Zealand for the local cultivar 'Inulinz'. Further testing will be needed to define how far north the crop can be grown and still have buds vernalised to enable good perennial vegetative yield. The costs for planting and storing tubers need to be determined. Management practices need to be defined to ensure tubers do not regenerate if paddocks are used for different arable crops. No issues noted to date appear to seriously detract from this species' potential in the majority of New Zealand (Fig. 5).

4.1.4 Switchgrass (*Panicum virgatum*)

Criteria match for dry mass yield: Switchgrass has been widely tested in its native North America and its yield potential modelled throughout the USA (McLaughlin and Kszos 2005; Wright et al. 2009). Test yields ranged from 4 to 18 t DM/ha and were most often in the 10–12 t DM/ha category (Wright et al. 2009). Greater yields were sometimes observed in the southeast region of the USA with the hottest summer weather and ample rainfall. It was lower yielding than Miscanthus in direct comparisons (Heaton et al. 2008).

Agronomy: Switchgrass has a low nitrogen requirement and moderately lower water requirement, which is similar other C4 species such as Miscanthus. It persists for at least 10 years and is easy to maintain.

Issues: Switchgrass is not currently in New Zealand and would probably not qualify for introduction since it is able to spread by seed as well as rhizomes. Growth would start very late in the spring due to cool New Zealand soils and high yields would be unlikely in the temperate summer weather. Yields would also likely be low in marginal sites with low summer rainfall (Ceotto and Di Candilo 2010).

4.1.5 Reed Canary Grass (Phalaris arundinacea)

Criteria match for dry mass yield: Reed canary grass is present in New Zealand and was tested as a feedstock for biogas production in the 1980s (Stewart 1983). It is

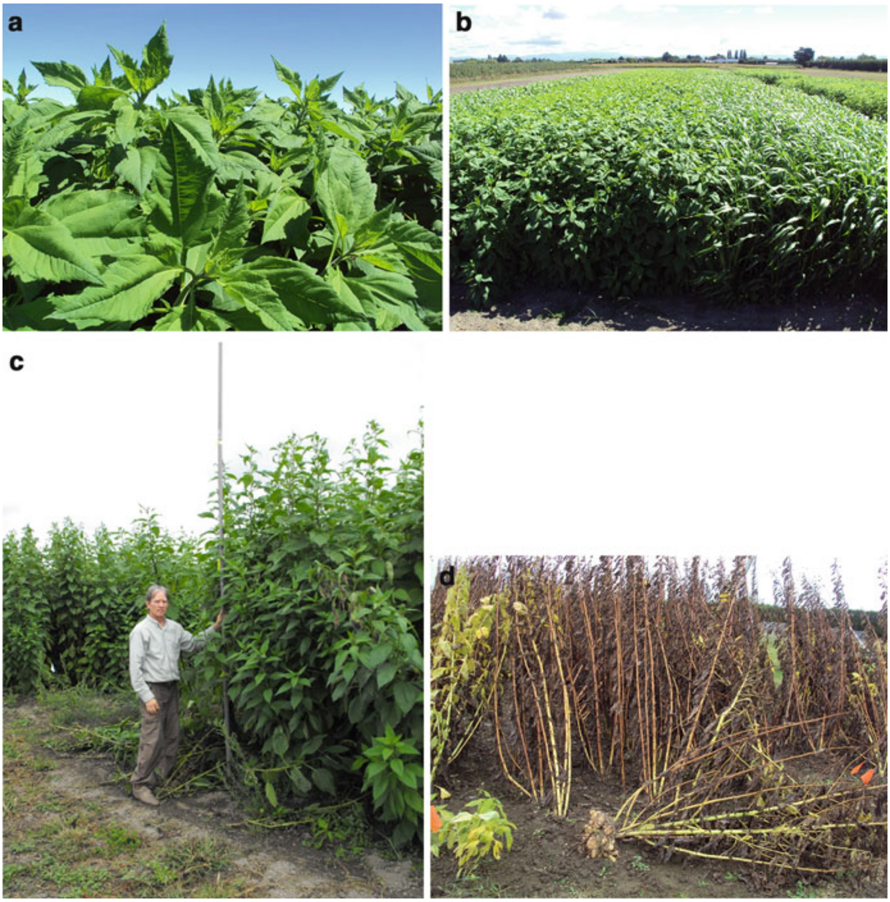

Fig. 5 Jerusalem artichoke (*Helianthus tuberosus*). Vegetative growth is rampant even in cool weather (**a**) and in Hawke's Bay region is similar to the growth and mid-summer mass of the sorghum on either side (**b**). Shoot dry mass peaks after flowering (**c**) and shoot mass is translocated to the tubers from the stage in **c** through to shoot senescence (**d**)

very hardy, grows quickly and spreads easily both by seed and by creeping rhizomes. Dry mass yield under European conditions was less than 10–12 t DM/ha in a comparison to Miscanthus and triticale (Lewandowski and Schmidt 2006).

Agronomy: The species is an inferior crop to Miscanthus in the climates of north-western Europe in terms of nitrogen use efficiency and energy use efficiency (Lewandowski and Schmidt 2006).

Issues: Reed canary grass is considered to be a weed pest in New Zealand wetlands. It is a major threat to marshes and wetlands because it can replace native species. It is difficult to eradicate once established and there could be a problem for local authorities. It is currently listed for eradication (Environment Canterbury 2011).

Fig. 6 Harding grass (*Phalaris aquatica*). Like other perennials Harding grass makes a slow start compared to the surrounding forage oat crop, planted at the same time. It grows 1.5–2 m tall, but is not higher in dry mass than shorter pasture grasses

4.1.6 Harding Grass (*Phalaris aquatica*)

Criteria match for dry mass yield: Harding grass is a tall bunchgrass of the same genus as canary reed grass. It is present in New Zealand and has been sown in pastures as a 10% component of seed mixtures. It is toxic to cows at higher levels, so the only information on its growth in pure stands was from a seed grower. Preliminary results were also obtained in a small research trial in the Hawke's Bay region (unpublished). At the end of the first season (November 2009) the Harding grass yielded much lower than plots of winter annual oats in the same trial. Harding grass produced (5.0 ± 2.2 t DM/ha) compared to oats (16.9 ± 4.3 t DM/ha). In the following season the Harding grass plots were damaged, but they would have been expected to yield between 7 and 12 t DM/ha based on the long-term experience of a New Zealand seed grower (Ian Gorton, personal communication, 2009). It was clear that annual DM yield from perennial Harding grass would be far less than the combined annual yield of winter oats and a summer biomass crop. Such a large yield deficiency outweighs the benefits of using this perennial species for biomass production.

Issues: *Phalaris aquatica,* while tall-growing, has no greater dry mass than the best regular pasture grasses and it is toxic to livestock if there is >10% in pastures (Fig. 6).

4.1.7 Napier Grass (*Pennisetum purpureum*)

Criteria match for dry mass yield: Napier grass is a large perennial that can grow more than 3 m high. The leaves are susceptible to frost but the root system can remain alive if the ground is not frozen. The grass grows easily from rhizome and stem fragments and forms thick clumps with long, flat leaves which have strongly ridged midribs. Napier grass is present in New Zealand and has been tried as a biofuel feedstock (Stewart 1983).

Issues: Napier grass is listed as a pest species in New Zealand and classified as an Unwanted Organism by the Department of Conservation (Biosecurity NZ 2011b) and is also listed as an invasive species in the Pacific Islands.

4.1.8 Cardoon or Cynara (*Cynara carduncululus*)

Criteria match for dry mass yield: Cynara (or cardoon or artichoke thistle) is a tall relative of artichoke used as an ornamental or for edible stems by those tolerate the sharp thistle features. It is known for its high biomass yield (>25 tDM/ha) under favourable conditions (Angelini et al. 2009; Gominho et al. 2011).

Physiology: Recent research into dynamics of light and nitrogen distribution in canopies (Archontoulis 2011) provided a basis for the high dry mass yield of cardoon in relation to other biomass species. The crop is very well suited to the Mediterranean climate with rainfall concentrated in the early part of its season, but in drier years may need irrigation in springtime for high yield (Archontoulis 2011). This last reference also contains photos of Cynara and kenaf.

Cardoon is costly to establish, although somewhat invasive once present. Crop handling needs to allow for its sharp spines and cardoon has higher nutrient requirements than ideal for a biomass crop. The biomass may be too high in ash content for gasification. The climatic preference is for very dry summers which are rare in New Zealand. If there is rain after the crop starts to dry it may regrow. That could make the harvested biomass too wet for storage or gasification. In one LCA analysis of four biomass species in Italy the cardoon was far worse than the other three in terms of its impacts, on an energy basis (Monti et al. 2009).

4.1.9 Giant Reed (*Arundo donax*)

Criteria match for dry mass yield: Giant reed is a clump-forming bamboo-like grass having short rhizomes and a dense root mass. It can grow up to 5 m in height. Giant reed does not spread by seed and has very high biomass yield (>25 tDM/ha) in Mediterranean climates (Ceotto and Di Candilo 2010).

Issues: Giant reed requires abundant moisture and is subject to serious damage by spring frosts. It has an ability to spread over geographic locations quickly, via natural waterways, which allows Giant Reed to overtake large areas very quickly. Giant Reed is an extremely flammable plant, even when it is green. These factors produce various results that make Giant Reed extremely undesirable in New Zealand where the winters are milder than in Europe. It is already present but the subject of control efforts (Biosecurity NZ 2012a; New Zealand Biosecurity Institute 2009).

4.1.10 Tagasaste or Tree Lucerne (*Chamaecytisus palmensis*)

Criteria match for dry mass yield: Tagasaste or tree lucerne has been studied for forage use in New Zealand (Logan and Radcliffe 1985; Lambert et al. 1989). The per-plant yields were rarely converted to yield per hectare; the only cited value was <2 tDM/ha. Tree height in experiments was less than 2 m.

Issues: Tagasaste had low yields in many years due to drought sensitivity. In warm wet conditions it was susceptible to root rots (Logan and Radcliffe 1985).

4.1.11 Pampas Grass (*Cortaderia sellowana*)

Criteria match for dry mass yield: Pampas is a giant, clump-forming grass that can grow to 4 m or more. The leaves snap readily when tugged. Dead leaf bases curl like wood shavings, unlike the related native *C. fulvida*. No annual dry mass data is available in New Zealand.

Issues: Windborne seeds allow the grass to easily spread far and wide. It readily colonises disturbed sites, quickly becomes dense and can suppress the growth of other species. It replaces ground cover, shrubs and ferns, creates a fire hazard, provides habitats for possums and rats, and impedes access (Biosecurity New Zealand 2011a). It is therefore classified as a noxious weed in two regions. It would be restricted from use as a biomass crop.

4.1.12 Toe toe (*Cortaderia fulvida*)

Criteria match for dry mass yield: The New Zealand native species of *Cortaderia* are smaller than pampas grass. No dry mass yield per hectare has been reported, but it is visually much less massive than pampas grass.

Issues: Native *Cortaderia* species are slow to establish and there are restrictions against the use of non-local ecotypes of this native species in some areas, according to New Zealand specialist W. Parker of Oratia Native Plant Nursery (personal communication, 2009).

4.1.13 "Wandering willie" (*Tradescantia fluminensis*)

Criteria match for dry mass yield: *Tradescantia,* is a rank perennial weed in shady areas but it is low growing and is not a high dry mass producer, only 7.5 tDM/ha (Standish et al. 2001). *Tradescantia* was impressive in terms of efficient use of low solar radiation, with its dry mass peaking at only 10% of full sunlight.

Issues: There could be restrictions on its cultivation and distribution due to its adverse impact on natural wooded landscapes. In the sun it would probably be overgrown by other species.

Fig. 7 Yacon (*Smallanthus sonchifolius*). Yacon is grown for its crisp root and also has massive shoot growth, but which is quite reduced by root harvest time. Note the frost burn of upper leaves

4.1.14 Yacon (*Smallanthus sonchifolius*)

Criteria match for dry mass yield: Yacon is a tall-growing perennial (2 m) with very large shoots. Their mass has not been measured in New Zealand at the peak time during the summer in a research report that focused on fresh mass of the large fleshy (edible) storage roots. At harvest time fresh mass of shoots was 15.7 t FM/ha compared to 90 t FM/ha in roots (Douglas et al. 2007). Even if the standing shoots had air dried to a moisture content of 50% before harvest the DM yield would have been <8 t DM/ha.

Agronomy: New Zealand trials found that yacon requires early spring planting and a long season to achieve high root fresh mass yields; in cooler areas the root yield was only 20–30% of the top yield in a warm site (Douglas et al. 2007). Therefore only latitudes below 38° should be considered suitable in New Zealand. Warm nights may be required for higher shoot dry mass, but these are lacking in most of New Zealand.

Issues: Yacon is quite frost tender, part of the reason most of New Zealand is considered unsuitable. The use of roots for biomass requires too much energy expenditure for harvest and there is as yet no market in New Zealand for the roots as food. This would be a prerequisite for using the shoots as a crop residue (Fig. 7).

4.1.15 Water Hyacinth (*Eichhornia crassipes*)

Criteria match for dry mass yield: Water hyacinth is a mat-forming water weed with very high productivity.

Issues: Water hyacinth entered New Zealand many years ago and became a pest species. Its current status is that it has been eradicated and has not been allowed into New Zealand since 1927, eliminating it from contention as a biomass species (Biosecurity New Zealand 2012b).

4.1.16 Cattail (Rapu in New Zealand) (*Typha orientalis*)

Criteria match for dry mass yield: The native species of this genus has the Maori name rapu. Its common name in North America is cattail and in the UK bulrush. Rapu is closely related to those northern hemisphere *Typha* species, which have been studied in relation to bioremediation of secondary sewage and for biofuel production (Shahbazi 2009). The biology of *Typha orientalis* has been detailed in northern New Zealand (Pegman and Ogden 2005), where its annual dry mass productivity was 29.1 t DM/ha, with 22.6 t DM/ha in the shoots.

Agronomy: Both due to its very high DM productivity and adaptation to sites not suited for food crops, rapu is an interesting biomass weed to consider cropping. Since many natural wetlands would be excluded from harvest for environmental reasons, commercial production of rapu would probably be on marginal, poorly drained agricultural land and this would require special landform modification to create standing water. Some current dairy pastures in the South Island West Coast, shaped into 'humps and hollows,' already have nutrient runoff problems in the hollows, so nutrient interception by rapu could make milk production more sustainable while producing biomass.

A preliminary trial in the Hawke's Bay region compared quadrat harvests in a wetland, either a two cut per season regime or a single early winter harvest. The mean DM yields were a total of 18.6 t DM/ha for the two cut regime compared to 29.7 t DM/ha for the one cut regime (unpublished data). So rapu has a very high peak shoot DM which is adversely affected by an additional summer harvest.

Issues: Like Miscanthus (Clifton-Brown et al. 2004), the ideal timing for first biomass harvest may not be at the early winter peak dry mass, since that may reduce the yield in the following season. So some loss of shoot dry mass via translocation to the rhizome system prior to harvest is probably necessary. The requirement for standing water, coupled with the legal protection of natural wetlands, very much limits the scope for commercialisation of *Typha* as a biomass crop. Harvest would be more feasible in climates colder than New Zealand, where ponds freeze hard enough for driving equipment on the ice (Fig. 8).

4.1.17 Gorse (*Ulex europaeus*)

Criteria match for dry mass yield: The average DM yield over a 6-year growth cycle reported in a lower North Island study (Egunjobi 1971) was 9.8 t DM/ha/year plus average annual litter fall of 8.9 t DM/ha/year. This was calculated from the 60 t/ha standing biomass at age six, measured for plants that grew from seed after the site

Fig. 8 Cattail or Rapu (*Typha orientalis*). This wetland weed has a very high peak dry mass, but harvest probably needs to be delayed past the peak

was burned. A goat forage trial in the Canterbury region found the DM yield to be 19.5 t/ha/year (Radcliffe 1986). Gorse as biomass crop has strong appeal due to its wide adaptation, growth on sloping marginal land, coppicing ability and need for little or no fertiliser. It is also a legume that fixes nitrogen, sometimes enough to create a nitrogen run-off problem.

<u>Agronomy:</u> Gorse grows well on steep slopes in New Zealand, a category of clearly marginal land that cannot be used by most biomass crops which require slopes suitable for harvesters. It would be harvested more like a short-rotation forestry crop and would regrow from cut stems.

<u>Issues:</u> Gorse's shortcomings as a biomass species include its lesser harvestable dry mass (since litter would be difficult to collect) and practical management difficulties such as its nasty spines. If this species' potential was deemed worthy the latter might be overcome by in vitro plant breeding to develop a spineless form.

4.2 Summer Annual Species

4.2.1 Maize (*Zea mays*)

<u>Criteria match for dry mass yield:</u> Very high DM yields, many in the 25–30 t DM/ha were documented in New Zealand seed company field trials (Densley et al. 2005) and also in research trials (Booker 2008; Li et al. 2006; Reid et al. 1999; Rhodes

1977; Shaw et al. 2007). A 2009–10 trial at two marginal sites produced maize yields of 29 t DM/ha in the irrigated site and 12.6 t DM/ha in the drought-affected site (Kerckhoffs et al. 2011). The high yield and strong knowledge base (as a major New Zealand crop for grain and silage) makes maize a good benchmark to compare other summer annual biomass species to.

Agronomy: Silage maize is well-studied in New Zealand (Booker 2008; Li et al. 2006; Rhodes 1977; Sadras and Calvino 2001; Shaw et al. 2005a, b, 2007). Even in a drought year in the Waikato maize region (2007–08) the mean biomass yield across 44 trials of Pioneer® seed was 22.3 t DM/ha (B. McCarter, Genetic Technologies Ltd, personal communication) Maize response to nitrogen supply has been characterised in the New Zealand crop model AmaizeN (Li et al. 2006) and response to soil water supply has been widely studied (e.g., Sadras and Calvino 2001).

Issues: Maize is high yielding and its agronomy is well defined, and therefore a good species for assessment as a gasification feedstock in the planned engineering model in the research project. However, there are issues with its large scale use as a biomass crop. The main issue is an ethical one (discussed in Sect. 3). Maize is grown on the best arable land that could be producing important food crops. Its main use is as a feed crop (either forage or grain) for livestock; the end products are milk and meat. At the scale of New Zealand alone this is not an ethical issue, since about 90% of the meat and milk is exported and any staple food can be locally supplied to meet New Zealand food demand. At the global scale the need to increase food supply does make this an issue, although the protein foods are exported to populations already well fed, not those that are hungry (Fig. 9).

4.2.2 Sunflower (*Helianthus annus*)

Criteria match for dry mass yield: There is no published research on sunflower biomass yield in New Zealand and the international literature is predominantly on seed and oil production. The reported DM yield in Perth, Australia was 14 t DM/ha (Steer et al. 1993) and the yield was similar in Oregon, USA trials (Kiniry et al. 1992). Yield was 11 t DM/ha in Victoria, Australia (Connor et al. 1985). Dry mass yields were 10.8 t DM/ha in research in Turkey (Goksoy et al. 2004) and 12.8–13.9 t DM/ha in a study in Greece (Archontoulis 2011).

A 2005–2006 trial by the authors with a forage sunflower cultivar in a fertile Hawke's Bay soil yielded up to 17 t DM/ha at the highest plant population density among several densities that were compared (the overall average yield was 14.4 t DM/ha). This crop had a very high average growth rate of 173 kg DM/ha/day (unpublished data). A 2009–2010 trial at two marginal sites produced sunflower yields of 10.4 and 8.1 t DM/ha (Kerckhoffs et al. 2011). The limiting factor was loss of the seed to birds in one location, since seeds are typically 25% of the total dry mass (Massignam et al. 2009). At the other site the low yield was due to severe water deficit (Fig. 10).

Agronomy: Sunflower has potential as a biomass species due to its moderate dry mass yield in mildly marginal conditions and a relatively short growing season.

Fig. 9 Maize (*Zea mays*). Selection '33 M54' is a long-season type and yielded 33 t DM/ha 2 months after this photo in Northland

Fig. 10 Sunflower (*Helianthus annum*). Forage sunflower had lower dry mass than other species tested and has about 25% of its dry mass as seeds, which can be lost to birds

Since the aim of biomass production is to maximise sustainable yield on a year-round basis, a species with a fast growth rate that fits between other crops can satisfy a useful purpose. The irrigation response by sunflower has been studied in the Mediterranean (Goksoy et al. 2004; Sadras and Calvino 2001) and Australia (Connor et al. 1985).

Physiological aspects: In addition to soil water response (Connor et al. 1993; Steer et al. 1993) the effects of canopy architecture are very relevant to sunflower dry mass yield potential (Archontoulis 2011). Both of these high dry mass factors are less optimal in sunflower than in very high dry mass species such as cardoon and kenaf (Archontoulis 2011).

Issues: The greater drought susceptibility of sunflower than several high dry mass C4 grasses such as sorghum, maize and pearl millet makes it less adaptive to marginal soil water supply. The significant part of the total dry mass in the seeds (and the high risk of losing it to birds) and the somewhat lower dry mass yield even in good conditions are all negative factors for sunflower biomass production.

4.2.3 Sorghum (*Sorghum bicolor*)

Criteria match for dry mass yield: Dry mass yield of fibre sorghum in the north of Italy was 26.2 tDM/ha (Amaducci et al. 2000). High yields were also observed in Greece (Danalatos et al. 2009). The cooler New Zealand climate might be expected to limit yields and that has been the case based on the average yield of 15.5 tDM/ha from several NZ science reports (Cottier 1973; Taylor 1973; Taylor et al. 1974; Chu and Tillman 1976; Rhodes 1977; Piggot and Farrell 1980; Causley 1990). However, the mean would be much lower without the results in the reports by Piggot and Farrell (1980, 1984) who found that 'Sugar Drip' sweet sorghum averaged 25 tDM/ha in deep loams and well-drained fertile clays and 20 tDM/ha in dry friable soils in Northland, the warmest part of New Zealand. In the authors' 2010 trial in Northland the yield of the best subtropical sorghum cultivar was 30.3 tDM/ha (see Table 4) (Kerckhoffs et al. 2011).

Agronomy: Sorghum is not widely grown in New Zealand but its use for dairy forage is of current interest to farmers. It is generally found to yield lower than silage maize but to have greater drought tolerance and ability to recover (Singh and Singh 1995). Hybrid sorghum cultivars fall into three categories: sorghum x sorghum, sorghum x sudan and sudan x sudan crosses. New subtropical cultivars require testing of their potential to stay in vegetative mode for an extended period, increasing the biomass yield. Tests in Australia indicated high total dry mass from use of multiple cutting, for grazing as dairy feed (Johnson 2005). In the cooler New Zealand climate a higher total dry mass may be expected from a single harvest of a long-season cultivar. Effective weed control in this small-seeded crop is of agronomic importance, but provided by current herbicides.

C4 grass species usually have very high nutrient input requirements. The 'rule of thumb' of the seed company supplying the best two sorghum cultivars is that a 30 tDM/ha forage crop would remove over 500 kg/ha of nitrogen, even if a subtropical species does not produce seed. However, tissue analyses from our Northland field trial (Kerckhoffs et al. 2011) indicated that crop removal was only 240 kg N/ha.

Physiology: One feature of sorghum conducive to its use in marginal sites is better tolerance of and recovery from soil water deficit. Studies in Greece (Dercas and Liakatas 2007), India (Singh and Singh 1995) and the USA (Stone et al. 2002) have helped clarify agronomic response and physiology of water use. Nitrogen use by plant parts is another relevant aspect (van Oosterom et al. 2010) as is the effect of sowing rates on biofuel productivity (Wortmann et al. 2010).

Issues: While sorghum may grow well in conditions of low water availability, the main apparent drawback to use of sorghum for biomass production in New Zealand is that much of the country does not have warm enough temperatures for a long enough growing season. The suitable regions are below latitude 38° S. These include Northland, Waikato, Bay of Plenty, East Cape and Hawke's Bay. However, regions other than Northland could be cool enough some years to impact yields. Several of these regions have enough summer rainfall that the choice of 'marginal sites' may need to be based on yield restrictions other than soil water deficit, such as more frequent site susceptibility to cool weather. As with other agricultural crops there is also the issue that the use of sorghum as an energy crop competes with its use for livestock forage. Sorghum also has a high nitrogen fertiliser requirement. Although our trial measured nitrogen uptake by a fully matured crop to be only 240 kg N/ha, this level of nitrogen use is still an issue for a biomass crop unless the fuel conversion technology conserves nutrients. Gasification does not do so (Fig. 11).

4.2.4 Pearl Millet (*Pennesetum glaucum*)

Criteria match for dry mass yield: There has been very little use of this crop species in New Zealand, particularly for full season growth to its maximum biomass. Yield reports in Australia are on grain yield rather than biomass (Queensland Primary Industries and Fisheries 2005; Pacific Seeds 2009). Cultivars for feed seed production are short in both height and season, so forage cultivars are preferable for biomass. The potential for pearl millet to have a high yield in northern New Zealand is based on its height and growth similarities to sorghum in Australia (Pacific Seeds 2009) and on high sorghum yields in past New Zealand trials (Piggot and Farrell 1984). In the authors' 2010 trial in Northland the yield was very high, 31.2 t DM/ha (see Table 4) (Kerckhoffs et al. 2011).

Agronomy: When grown for biomass the cultural methods used are essentially the same as for subtropical cultivars of sorghum. Most information is directed at the feed quality of Pennesetum when used as forage, eg, in Queensland, Australia (Pacific Seeds 2009). The low protein content of pearl millet when grown all season rather than grazed is indicative that the nitrogen fertiliser requirement is likely to be much lower than when grown to be grazed.

Fig. 11 Sorghum (*Sorghum bicolor*). In the cooler climate of the lower North Island a sudan x sudan hybrid cultivar like 'Sprint' only yielded about 7 t DM/ha (**a**). In Northland the subtropical cultivar 'Jumbo' had a 30.3 t DM/ha yield 2 months after the photo (**b**)

Pearl millet has been found to be even more adaptive to soil water deficit than sorghum, at least in terms of grain production (Queensland Primary Industries and Fisheries 2005).

Issues: Like sorghum, pearl millet is an agricultural crop whose use as an energy crop competes with its use for livestock forage. The moderately high fertiliser inputs will require special crop management and end use of the biomass to make production sustainable (Fig. 12).

Fig. 12 Pearl millet (*Pennisetum glaucum*). The cultivar 'Nutrifeed' yielded as well as the subtropical sorghums in Northland (31 t DM/ha) 2 months after the photo

4.2.5 Hemp (*Cannabis sativa*)

Criteria match for dry mass yield: Hemp is a tall-growing short-season species grown for fibre or oil, including to a limited extent in New Zealand (McIntosh 1998). Research has focused on the production of fibre and seed oil, not biomass (McPartland et al. 2004) however the crop has reportedly yielded >20 t DM/ha in Italy, 19 t DM/ha in the Netherlands and relatively well on marginal sites (Struik et al. 2000). Models have been developed of both growth and industrial economics (Eerens 2003). The highest dry mass yields will probably come from different cultivars than used for oil and fibre. The few published reports of New Zealand dry mass yield (McIntosh 1998; Gibson 2007) indicated a wide range of yields, only the upper end of which makes hemp of interest as a principal summer crop for feedstock for gasification or other biofuel technologies. Yields of 14–20 t/ha were cited, but in several experiments they were <10 t/ha. However, industrial hemp could fill a useful niche in a biomass system since it achieved its maximum yield in a shorter time than other crops, perhaps enabling it to be grown between two high-yielding winter crops.

Recent New Zealand field measurements of dry mass, commissioned by the author in 2010, were made by Midlands Seed Ltd near Ashburton in the South Island. In plots harvested from a fibre cultivar the dry mass yield averaged 9.1 t DM/ha

Fig. 13 Hemp (*Cannabis sativa*). The height difference between an oil seed cultivar (*centre*) and the more suitable fibre cultivars (Photo courtesy of Midlands Seed Co., Ashburton, New Zealand)

(unpublished data), well below the 15 tDM/ha target deemed economically viable for summer annual crops to supply bioenergy facilities.

Agronomy: To achieve high dry mass may require sowing seed at quite a high rate (Struik et al. 2000). Nitrogen fertiliser above 100 kg N/ha had no benefit to dry mass yield (Struik et al. 2000). Hemp is also fairly adapted to periods of water deficit. A study of the economics of growing hemp fibre as a crop for land treatment of treated sewage (Eerens 2003) determined that it would be difficult even in the central North Island to produce two crops (two cuttings) as would be required for an economically viable treatment and fibre production system.

Issues: The largest hurdle to New Zealand production of hemp is the regulatory compliance costs of its growth, storage and shipment to ensure the crops do not contain illegal levels of drug THC, as found in other *Cannabis sativa* cultivars. There is also the need to document high yields in cooler South Island sites, where its use as a short crop between winter forage, grain or biomass crops would be most valuable. The best yields would be in northern New Zealand, but there are better species options there (Fig. 13).

4.2.6 Kenaf (*Hibiscus cannabinus*)

Criteria match for dry mass yield: Kenaf is a warm season annual species that grows very tall (>4 m in hot climates) with a high dry mass yield potential (Alexopoulou et al. 2000; Danalatos et al. 2006), Yields in a recent irrigation trial ranged across 19.6, 22.8 and 24.5 tDM/ha (Archontoulis 2011). Past research in New Zealand for use as paper pulp showed that in the cooler local climate the yield was <9 tDM/ha and the height was <1.7 m (Withers 1973).

Physiology: Canopy architecture findings help explain the high yield potential in the Mediterranean climate (Archontoulis 2011).

Issues: Kenaf requires warmer summers than occur in New Zealand. It is also susceptible to Botrytis infection and prone to keep growing if water is available, as is likely here. That may make it difficult to get the biomass dry enough for harvest.

4.3 Winter Annual Species

4.3.1 Tickbean (*Vicia faba*)

Criteria match for dry mass yield: Vicia faba (broad bean, fava bean) is a winter crop that has been reasonably well-researched as a forage crop in New Zealand. The dry mass yields reported in the South Island experiments were always less than 15 t DM/ha (Jones et al. 1989; Newton and Hill 1987; Rengasamy and Reid 1993). A 2011 Hawke's Bay trial with the cultivar 'Wizard' sown on 11 April and harvested 28 October yielded an impressive 24 t DM/ha (data not yet published).

Agronomy: Tickbean is of interest as a winter crop in rotation with a late-sown or short-season summer annual. This would be most feasible in regions with sufficient summer rainfall, such as Southland and several parts of the North Island. It is sown as early as possible in autumn after previous crop removal (e.g., April in New Zealand). Its cultural requirements have been described (Rengasamy and Reid 1993; Jones et al. 1989; Newton and Hill 1987). For use as forage it is harvested prior to its peak seed maturity when the feed value is not reduced by lack of water. Even for a mature harvest the soil water supply is only likely to be an issue during a rare winter drought in the eastern cropping districts of both North and South Islands. Nitrogen is fixed in the root system nodules.

Issues: Although the dry mass yield was very high in the 2011 trial, the favourable weather conditions, the timing of crop development and lack of disease may be hard to duplicate. It could be challenging to grow in marginal soil and colder South Island winters and still fit between summer crops, which also take longer in the cooler weather. In the wet winter climate there is a significant cost in keeping diseases such as chocolate spot under control. The tissue water content at harvest may also be higher than ideal for a biomass crop (Fig. 14). However, this species should be considered for the lower South Island.

4.3.2 Winter Cereals: Wheat (*Triticum aestivum*), Oats (*Avena sativa*), Barley (*Hordeum vulgare*) and Triticale (x *Triticosecale*)

Criteria match for dry mass yield: Cereal species sown in autumn or winter and harvested in early to mid summer have been shown to yield >15 t DM/ha in good arable soils in New Zealand. Dry mass yield is reported as 'whole crop yield' in cereal research, where grain yield is usually the focus. Winter wheat can have a

Fig. 14 Tickbean or broadbean (*Vicia faba*). A tall dense crop after a warmer than average Hawke's Bay winter growth season

whole crop yield >15 t DM/ha (de Ruiter 2004; Kerr and Menalda 1976; Stephen et al. 1977). Forage oats yielded 16.9 t DM/ha in the author's 2009 trial (unpublished), similar to other North Island findings (Kerr and Menalda 1976; Stephen et al. 1977; McDonald and Stephen 1979). Winter barley dry mass yields were 14.7–16.6 t DM/ha (Kerr and Menalda 1976; Scott and Hines 1991). Triticale whole crop yields can be >20 t DM/ha, both in the North Island (Scott and Hines 1991) and the southern South Island (Plant & Food Research unpublished trial results for clients). All results are yields on good arable crop land.

Agronomy: There is an active research programme that has documented soil water and nitrogen fertiliser responses in terms of grain yield (e.g., Carter and Stoker 1985). The research cited in the previous paragraph documented high biomass production of these cereal species for forage in New Zealand. The geographic focus for use of winter annual species as energy crops is the South Island, where species that require warmer conditions (such as sorghum) are not feasible. The main effort required to assess triticale (or other cereals) as energy crops is to determine their yields in marginal New Zealand sites, via research trials and/or use of crop models.

Issues: If dry mass yield is determined to be adequate (>13 t DM/ha may be sufficient if production costs are moderate) then the main issue is whether food/feed species should be used as energy crops. Another issue is the nitrogen fertiliser requirement,

Fig. 15 Triticale (*x Triticosecale*). The vegetative growth of triticale (at the rear) is much greater than the modern wheat in the foreground, and dry mass is also greater

which may be high with some cereals. If economic supply of feedstock to a gasification plant requires double cropping (having a short summer crop between winter triticale crops) then the feasibility of this, using 'marginal' sites, is also a relevant issue (Fig. 15).

5 Rapid Species Selection Approach

The review of literature presented above was the central element in meeting the first 2 year aim of a 6 year research project. However, the review was not in itself sufficient for the project aim and it was also tailored to be integrated with local New Zealand information on the performance of plant species. The aim was to obtain a reduced list of high dry mass species with suitable attributes.

A final 'short list' of the best species was reached in two steps, starting by excluding less suitable species until there was a manageable number remaining (termed pre-selection). This involved three elements, the principal one being the science literature review that is the focus of this paper (Sect. 5.1). The following two subsections describe the use of New Zealand expertise and the use of conceptual tools to structure the species comparisons using the literature information. The last element of pre-selection was the gathering of new preliminary field measurements (Sect. 5.4) to help identify the most promising 15 biomass species for the intended end use.

More detailed evaluations of the 15 pre-selected species included two additional procedures, a formal field trial in two climatic zones (Sect. 5.4) and the use of crop models (Sect. 5.5). Overall, our species selection approach may be novel in its integrated use of procedures that were all capable of delivering results within a 2-year timeframe. Sections 5 and 6 are therefore presented for the benefit of readers that may face similar time constraints in selecting among plant species for a particular use. Sections 5 and 6 therefore have more aspects of a 'Methods' paper than would usually be found in a review.

5.1 Pre-Selection of High Dry Mass Species Via Literature Review

A species selection approach with a step-wise structure was developed to achieve the project aims. The first step was a pre-selection of promising high dry mass species based on the international literature, as cited in the subsection for each species listed in Sect. 4. When a species was a widely-grown New Zealand agricultural crop then the literature review was used to specify attainable dry mass yield. Relevant information was collated for biomass productive potential for specific regions within New Zealand for potential use as an energy crop via gasification. Such species could be ranked and the best few species and cultivars identified. However, it is possible that the ranking on prime crop land will differ from the ranking on 'marginal' sites, which is the end objective of the research project. So even for major crop species there was an additional step required to estimate 'marginal site' yield before the final ranking could be made.

When a reviewed species had a reported high productivity and was likely to be adapted to part of the range of New Zealand climates, but was not present in the country, then additional procedures were required to establish its productivity ranking within 2 years. Plant introduction through New Zealand's rigorous biosecurity procedures would usually take too long. If a species had been introduced in past years, or had entered New Zealand inadvertently, then regulatory guidelines could be examined to see if the species identified in the literature review would be accepted for commercial use over extended areas of the country.

5.2 Pre-Selection of High Dry Mass Species Via Local New Zealand Expertise

Gathering local expert knowledge involved an effort to tap the institutional memories of research organisations regarding more obscure species of minor crops or weeds known to produce high dry mass. Measurements of dry mass had been recorded but not always published. This work was largely done during 1975–1985, a time of strong interest in bioenergy in New Zealand as elsewhere, due to the oil supply crises. Additional expert New Zealand advice on major arable crops came from commercial sources such as seed companies. Their records for a major crop like maize contain yield data from hundreds of field plots.

5.3 Pre-Selection Tools: Plant Growth Categories and Benchmark Species

As noted at the start of Sect. 4, the process of ranking of species in terms of high dry mass process was facilitated by distinguishing three categories of growth habit: summer annual, perennial and winter annual species, enabling more direct comparisons. Within each category it was possible to choose one species with well documented high dry mass performance in New Zealand. These are referred to as benchmark species. The research and seed company trial findings for maize and lucerne documented that these crops, when grown on fertile land with good water supply, had higher dry mass yields than other current New Zealand crop species of their types. Silage maize was designated as the benchmark for summer annuals and lucerne as the benchmark species for perennials. Details were presented in Sects. 4.1.1 and 4.2.1. Most high dry mass winter annuals are cereal grain species. The designated winter annual benchmark species was wheat (Sect. 4.3.2). All three benchmark species also shared the advantage of having crop models that are calibrated in the major production regions of New Zealand.

5.4 New Field Trial Data in New Zealand to Supplement the Literature Review

There was also a strong case, in the interest of time, to generate new field trial data to include in the species selection process. When a species was present in New Zealand, but there was inadequate dry mass data to rank it relative to other species, we planted small field trials along with familiar reference crops in order to make preliminary measurements of dry mass. This was done concurrently with the first year of the literature review. Those measurements were part of the pre-selection phase.

In the second year, more formal field trials were carried out with the more promising summer annual species/cultivars among the most promising 15 species. These generated new and climatically-relevant scientific data that is now published, therefore available as a new addition to the literature review. Results were a key part of selecting the final short list of 'best' species to assess for use in the bioenergy engineering research project.

5.5 Crop Models as a Tool to Estimate Dry Mass Yield in 'Marginal' Sites and to Compare Species

While the use of models may seem more appropriate to describe in a research paper than here, using this tool in the species selection procedure was necessary and the results are therefore reviewed. The rationale is based on the need during the final stage of species screening to rank species on how well they yield in 'marginal' sites rather than in prime crop land. Use of such sites is a more sustainable basis for bioenergy production. For previously researched benchmark species the yield data is from trials in good quality arable soils, so each of these species had to be checked as to whether it really belonged in the final list. The way to do this was via use of the crop models that could simulate yield under the environmental conditions that make a site marginal. This enabled the following step which was to compare the biomass yields of new candidate species to the 'marginal site' yields of benchmark species.

The models currently used in New Zealand are species-specific and local calibrations from the farming systems tool known as APSIM (Keating et al. 2003) developed in Australia. The three growth limiting factors that can be altered in the crop models are soil texture or depth, air temperature and rainfall. If a target yield for biomass production is set, such as 15 tonnes dry mass per hectare (t DM/ha), then the combinations of the three factors that restrict yield to 15 t DM/ha can be identified for each cropping region of New Zealand. While a benchmark species was used for this, the information that is used to assess a new species of that same growth habit type is an empirically- defined set of site conditions that represents 'marginal'. The target of 15 t DM/ha was chosen because all three benchmark species have demonstrated yields several tonnes per hectare more than that (see species details in Sect. 4).

The final step in selection of the best three to four species (in addition to the benchmark crops maize and lucerne) was to make use of any APSIM models of benchmark or other species to make more direct comparisons of available yield data. The aim for the best 'new' species is to utilise them in the subsequent 4 years of agronomic research and modelling of biomass supply to a gasification plant.

6 Overview of Species Selection

6.1 International Literature Pre-Selection

The result of the literature review was a compilation of the best 15 species to compare in more depth and the exclusion of a number of other species without further assessment.

Table 1 lists the species whose dry mass yields have previously been measured in New Zealand. See Chap. 4 for details of the basis for excluding each species from further consideration in the project on gasification feedstocks.

Table 1 Plant species in New Zealand assessed in the literature review but not included among the 15 promising species pre-selected for further evaluation during the first 2 years of the project

Common name	Scientific name	Exclusion criteria
Tagasaste or tree lucerne	*Chamaecytisus palmensis*	Low temp and disease sensitive
Toe toe	*Cortaderia fulvida*	Conservation restrictions
Wandering willie	*Tradescantia fluminensis*	Pest restrictions; low dry mass
Reed canary grass	*Phalaris arundinacea*	Pest restrictions
Napier grass	*Pennisetum purpureum*	Pest restrictions in regions
Pampas grass	*Cortaderia sellowana*	Pest restrictions in regions
Yacon	*Smallanthus sonchifolius*	Low temp sensitive; low DM

Table 2 Plant species considered due to being grown for biomass/biofuel outside New Zealand. These were assessed via literature review and by checking their status with New Zealand authorities. They were excluded from further consideration by the gasification feedstock project (full reasons are in Sect. 4)

Common name	Scientific name	Exclusion criteria
Sugarcane	*Saccharum hybrids*	Low temp sensitive
Switchgrass	*Panicum virgatum*	Requires hot summers
Jatropha	*Jatropha curcas*	For oilseed, not biomass
Water hyacinth	*Eichornia crasspies*	Prohibited pest species
Giant reed	*Arundo donax*	Restricted pest
Cardoon	*Cynara cardunculus*	Spreads by seed
Kenaf	*Hibiscus cannabinus*	Hard to get dry at harvest

Table 2 includes some species favoured for use as biofuel feedstock in other parts of the world. Sugarcane is one of the best sources of biomass and ethanol but requires tropical temperatures (Brito Cruz 2009). Jatropha has great potential as an oil seed tree crop and its cultivation is expanding in India (Jatropha World 2012), however it is used for seed production, not as a species for high total biomass. The other species are each considered in Sect. 4, where the issues that preclude them from use for gasification in New Zealand are described. Cardoon, while having several issues (see Sect. 4) may have better potential than the other species on this list. However, there is no New Zealand source of seed to test it at the necessary scale.

The outcome of the review of international literature and New Zealand expert advice was to reduce the number of candidate species to the 15 listed in Table 3. This also shows the New Zealand data sources available to compare and screen these crops. Field data is mostly from maize and sorghum variety trials by seed companies.

The method for the evaluation of summer annual species (other than hemp) from Table 3 was a formal field trial in two of New Zealand's warmer regions, at sites with 'marginal' soil/rainfall features. Perennial species could only be assessed where mature stands of plants existed or by analysis of yield in the New Zealand

Table 3 Herbaceous species pre-selected for use in the study and the type/source and number of crop plots of each

Common name	Scientific name	Commercial field data	New Zealand literature data	Crop Category
Lucerne	*Medicago sativa*	0	12	P
Harding grass	*Phalaris aquatica*	0	2	P
Miscanthus	*Miscanthus x giganteus*	0	0	P
Rapu	*Typha orientalis*	6	1	P
Gorse	*Ulex europaeus*	0	3	P
Jer. artichoke	*Helianthus tuberosus*	0	0	P or S
Maize	*Zea mays*	1054	7	S
Sorghum	*Sorghum bicolor*	64	11	S
Pearl millet	*Pennisetum glaucum*	0	0	S
Sunflower	*Helianthus annuus*	6	0	S
Hemp	*Canabis sativa*	1	4	S
Barley	*Hordeum vulgare*	0	26	W
Tickbean	*Vicia faba*	0	29	W
Triticale	*x Triticosecale*	0	8	W
Oats	*Avena sativa*	0	26	W

The three growth habit categories are Perennial (*P*), Summer annual (*S*) and Winter annual (*W*)

science literature. In some cases these results could be further refined by use of crop models. The timing of field trials for winter annual species, like perennials, did not fit within the 1 year available before a decision was required on the best four to six species, so ranking of these also relied on the New Zealand literature.

The cultivar choices in the trial with summer annuals were based on recommendations by researchers in the USA and Australia. We sourced seed of very high dry mass (usually subtropical) cultivars of C4 grass species of maize, sorghum and pearl millet. The trials also included sunflower and Jerusalem artichoke for use in cooler regions where the subtropical cultivars of C4 grasses would not be productive. A custom grower of the regulated species hemp was identified to make field measurements. The high DM clone of Miscanthus, *Miscanthus x giganteus* was also pre-selected for further investigation since its introduction to New Zealand was announced by a commercial venture (Brown 2009).

6.2 *Species Selection Among the 15 Most Promising*

6.2.1 Literature Review as Selection Basis

Among the species in Table 3 New Zealand literature was the basis to exclude some from the final list of three to four 'best' species for field testing as feedstock supply species for gasification. Those excluded from the short list were two perennials (rapu and gorse) and two winter annuals (barley and oats). The basis for these decisions is provided under *Issues* in each species' subsection of Sect. 4.

6.2.2 Field Measurements as Selection Basis

Preliminary field measurements led to the exclusion of Harding grass and hemp (see Sect. 4). Miscanthus was retained, even though it was not possible to establish a mature (3 year old) stand of the Mxg clone. The next best option was to calculate its biomass yield for several years with a crop model from the UK using the soil and weather data from a specific New Zealand site (see Sect. 4). The remainder of selection decisions were based on a field trial of summer annuals. The two sites were in Hawke's Bay and Northland (the warmest region, and where the trial site was irrigated due to below average rainfall). For details of the field trials see Kerckhoffs et al. (2011); other aspects will be reported in a subsequent research paper.

Table 4 provides evidence that the warmest region of New Zealand can produce very high DM yields of subtropical cultivars of maize, sorghum and pearl millet in sites with rooting depth restriction, provided rainfall is sufficient (or the crops are irrigated). All species at the Hawke's Bay site had very restricted yields in a year with an early summer water deficit, but results showed that some sorghum cultivars were much less affected than maize or pearl millet. Jerusalem artichoke was included in the trial since it can be grown as an annual.

The high yield results with tropical maize in the Northland trial confirm that maize was the correct choice as the benchmark species for summer annuals. The similarly high biomass yields with pearl millet and some sorghum cultivars also supports their consideration for use in New Zealand, although their geographic range is more restrictive than for maize. The performance of two sorghum cultivars in a drought situation is very promising for their use in marginal sites. Jerusalem artichoke also proved worthy of further investigation due to its modest nutrient and water requirements. In preliminary trials in Hawke's Bay and Canterbury the shoot dry mass yields were 15 and 17 t DM/ha, respectively (Kerckhoffs et al. 2011).

Sunflower was excluded from the final list of species for New Zealand following the field results in Table 4; the related species Jerusalem artichoke is more promising.

6.2.3 Ranking Procedures Among the Better Candidate Species

The species selection approach included making a yield estimate of species in marginal sites, in order to rank them to identify the best biomass crops for the intended use. This was done by the use of crop models, first applied to the benchmark species maize and lucerne. Their high yields in good arable sites were documented in Sect. 4. Section 7 summarises the application of APSIM models for the two benchmark species, maize and lucerne, to be presented in more detail in a research paper.

Table 4 Crop yields (t DM ha^{-1}) and dry matter percentages (DM%) at two locations

Crop	Cultivar	Northland Yield (t DM ha^{-1})	Northland DM (%)	Hawke's Bay Yield (t DM ha^{-1})	Hawke's Bay DM (%)
Maize	33 M54	33.7	45	13.2	37
Maize	38 H20	26.0	34	12	55
Sorghum	Bettagraze	19.5	27	11	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[a]	21	-	-
LSD		6.1	3	5.3	8.2
F-pr		<0.001	<0.001	0.005	<0.001

Table adapted from Kerckhoffs et al. (2011). LSD: least square deviation
Jerusalem artichoke yield is shoot dry mass only, excluding tubers

It then summarises the further use of models, where available, to compare short-listed biomass species candidates to the relevant benchmark crop yield in marginal sites.

The species selection procedure described in this Section was used by the authors to advise the Biofuels to Syngas to Liquid Fuels programme of the University of Canterbury as to which species should receive further research attention (Renquist and Shaw 2010).

7 Modelled Crop Dry Mass in Marginal Conditions

7.1 Models for Benchmark Species: Maize and Lucerne

It would be a multi-year task using field trials to estimate the dry mass yield of maize and lucerne under marginal conditions. Crop models are very useful to estimate yields under such conditions. Both species have crop models in the Australian crop model package APSIM (Keating et al. 2003) and each of them also has New Zealand calibrations.

New Zealand scientists have developed calibrations of APSIM models in the main arable cropping regions using both research and commercial trial data. While these calibrations are still being refined in order to use the models in very precise crop physiological applications, our use of APSIM was less demanding. The requirement was just for accurate enough yield estimates to rank species as having "higher, lower or similar" dry mass yields.

Soil water supply and temperature are two of the key defining parameters in the crop models, and for major crop species it is already known whether they are more sensitive to a deficit of water or warm temperatures. Marginal sites can often be categorised as yield-limiting due to one or the other of these two environmental factors.

The details of the APSIM model output graphs and the tables that illustrate whether or not an acceptable DM yield is achieved in each combination of site conditions are not shown in this review, but will be more fully explored in a research paper on this topic.

7.1.1 Maize (Summer Annual Benchmark Species)

The target yield for the summer annual benchmark, maize, was set at 15 t DM/ha, a somewhat arbitrary value but a yield that is likely to prove economically viable for biomass production. This is well below the maximum yield achieved in major North Island regions (see Sect. 4). The APSIM maize model creates an output graph for each region with a range of yields in response to soil water-holding (a combination of soil depth and texture) and rainfall and temperature (relative to the regional mean values). The target yield value may appear once or more in an output graph, which is examined to identify what combinations of non-optimal temperature and water deficit (a function of soil water-holding capacity and rainfall) are associated with yields reduced to that target level, but not below.

From the APSIM output graph and a table that is populated with the site conditions associated with the target yield of the benchmark species maize an appropriate conclusion can be drawn. One example is: "a 15 t DM/ha maize yield in Hawke's Bay region could be achieved without irrigation in a high water-holding soil even with 40% below-average rainfall when mean temperature is average or 1° above average." The site situations that are 'marginal' for maize in that soil category (having a dry mass yield equal to or less than 15 t/ha) are those with lower relative rainfall and/or with relative mean temperatures outside the optimum values shown. Non-optimal temperatures in New Zealand are usually lower than the optimum, but are in some cases higher.

In contrast to Hawke's Bay, a 15 t DM/ha yield of maize grown in the same soil texture in Canterbury requires 50% above-average rainfall and a temperature mean 1–2° above average. This comparison of climatic regions indicates that for a marginal site (without irrigation) in the shorter growing season of the South Island, the benchmark species maize will yield less than its North Island target yield under average rainfall and temperature conditions. This increases the chances that another species (adapted to a lower seasonal heat requirement) could match maize at these higher latitudes.

7.1.2 Lucerne (Perennial Benchmark Species)

For the perennial species growth habit category the benchmark species lucerne was assessed in the same manner as with maize. The shape of the biomass yield response graph looked similar to the one for maize (neither shown here), since the yields from all hay cuttings were combined.

While the regional differences in simulated yield for non-irrigated lucerne were not as great as the regional differences in maize dry mass production, the difference between the Hawke's Bay and Canterbury regions was still notable. The Hawke's Bay simulation indicated a yield of 15 tDM/ha could be achieved in high water holding capacity soils in a season with a temperature mean equal to the long-term average, even when rainfall was 50% below average. To achieve an equivalent yield in Canterbury required temperatures 1–3° above normal, with rainfall 20% above the long-term mean.

Lucerne is nevertheless a proven and well adapted crop to use as a perennial benchmark in the South Island, to allow comparisons with new perennial biomass species that are likely to be important for marginal sites. Lucerne could also serve as a benchmark for summer annuals in sites where the benchmark species maize may not be well suited.

7.2 Models for Comparing Candidates to Benchmark Species

The target yield for the summer annual benchmark species, maize, is 15 tDM/ha, as described in the previous subsection. Expressing the target yield in terms of yield-limiting environmental conditions enables a comparison to other summer annual biomass species, if their yields can be observed in conditions that would also limit the benchmark species maize to a similar yield (as simulated in the model). A summer annual biomass species that yielded 15 tDM/ha or greater under marginal (target yield) conditions would be well-ranked to receive more detailed further assessment.

7.2.1 Sorghum Versus Maize

There is an APSIM model for sorghum which allows a direct comparison to simulated maize yields. We calibrated the model for the Waikato region (the region closest to Northland where there were data to calibrate APSIM) in order to compare simulated yield results to those of the 2010–2011 field trial in Northland that contained both sorghum and maize. The maximum yields simulated in favourable conditions in the Waikato region were much higher for maize than sorghum (>25 tDM/ha versus 18 tDM/ha). But using the maize 'marginal' target yield of 15 tDM/ha (where the required Waikato region site conditions for maize were medium soil water-holding, rainfall 20% below average, and temperature 1° below average) the differences with sorghum were smaller.

The conditions in which sorghum achieved the 15 tDM/ha target yield were 50% less rainfall than average and mean temperature 1° above normal. Those conditions were wet enough for sorghum to match the 15 tDM/ha yield of maize, but they were

2° cooler than the sorghum optimum mean temperature. This was quite limiting and the sorghum model predicted a yield of only 12.8 tDM/ha. So in average Waikato weather the benefit of the drought resistance of sorghum is more than offset by its sensitivity to low temperature, even just 1 °C below average. If the models are accurate in this respect, it may explain the variable results with sorghum in most North Island districts. For example, the model predicted a large yield decrease (yield <50%) in sites that are 3° cooler than the optimum. This supports the findings of our 2009 field observations in the lower North Island (unpublished), where dry mass yield was less than half of the predicted Waikato yield.

The model analysis also highlights the importance of defining 'marginal' appropriately for the crop species and regional climate.

7.2.2 Sunflower Versus Maize

There is a sunflower model in the APSIM software, so it was possible to do a New Zealand calibration and directly compare sunflower to maize and sorghum yield simulations in the Hawke's Bay region. Even under the most favourable conditions maximum simulated sunflower dry mass yield was 11.4 tDM/ha. This underestimate is probably due to the model being developed using oilseed cultivars, which are more compact with lower dry mass than forage cultivars. But it also excludes the effect of bird predation on seed. This finding supports the field trial results (Kerckhoffs et al. 2011) where dry mass yield of a forage sunflower cultivar was lower than either maize or sorghum in both irrigated and non-irrigated trials.

7.2.3 Giant Miscanthus Versus Lucerne

The Mxg clone of Miscanthus is a very promising biomass species, so it was a priority to assess it as fully as possible during the species selection process. While there is no APSIM crop model, there is a Miscanthus model in the UK that was available to utilise for yield simulation (Hastings et al. 2009). The APSIM lucerne model also had a benchmarking role, to simulate the perennial species target yield in the appropriate climatic region for a yield comparison to the simulated average yield of Mxg at a particular site in that region.

The UK model for Mxg was applied to a specific site near Huntly in the Waikato region. Using soil information and meteorological records from the recommended station, the first author of the paper on the Miscanfor21SP model (Hastings et al. 2009) simulated the 13-year annual crop dry mass. The simulated peak dry mass in early winter averaged 27 tDM/ha, while late winter mean yield (the preferred time of harvest) was 18.7 tDM/ha.

The APSIM lucerne model, to compare to the Miscanfor21SP output, was calibrated for the Waikato using very similar but longer-term met data. The benchmark target yield is 15 tDM/ha in site conditions with 20% below average rainfall and a temperature right at the long-term mean. This is probably wetter than the 13-year data set used for the Miscanthus model (which included six dry years). The apparent conclusion is that Mxg is reasonably likely to exceed the yield of lucerne and is certainly worth undergoing further research.

7.2.4 Jerusalem Artichoke Versus Lucerne

An assessment was made to compare the promising new biomass species, Jerusalem artichoke, with lucerne. Informal yield comparisons in the Hawke' Bay region, where the most field data has been collected, have shown shoot dry mass yields near 15 tDM/ha in good arable soils (Kerckhoffs et al. 2011). This is higher than first-year yields of Hawke's Bay lucerne, but lower than the best lucerne yields in the second and third years (Shaw et al. 2005b).

Using the APSIM lucerne model, a target yield of 15 tDM/ha in Hawke's Bay region was associated with the following site conditions: High soil water-holding, rainfall 50% below average and temperature 1–2° above average. Jerusalem artichoke is, based on several studies (Kays and Nottingham 2008), able to grow well despite some water deficit and has high water use efficiency. It is also able to grow at cooler temperatures than many major crop species, having a heat unit base temperature of 0° for growth (Kays and Nottingham 2008).

While this is a new biomass crop in New Zealand, the preliminary conclusion is that shoot dry mass yield is similar to lucerne in Hawke's Bay region (Kerckhoffs et al. 2011). In the South Island, where non-irrigated lucerne yields in most soils are lower, Jerusalem artichoke has the potential to out yield lucerne. Field trials in the South Island, assisted by use of the APSIM model for lucerne, should clarify this matter.

7.2.5 Triticale Versus Wheat

The benchmark species chosen for the winter annual crop growth category is wheat. This crop is well-modelled in New Zealand using APSIM (Keating et al. 2003). While winter wheat cultivars have fairly high whole crop dry mass, e.g., 15.3 tDM/ha (Stephen et al. 1977), it is such a key direct human food crop that there would be market resistance to using it as a bioenergy crop species. Among the cereal grains triticale produces the highest dry mass yields in New Zealand, e.g., 22 tDM/ha (Scott and Hines 1991) and has the further advantage that it is not used as human food.

There is not yet an APSIM model for triticale, so a direct measure of its yield potential on marginal sites will require field tests. Wheat yields under marginal site conditions similar to those in the field trial can be estimated using the wheat APSIM model, or by including interspersed plots of wheat with the triticale.

8 Conclusions

This review of biomass species aimed to screen and rank candidate species in terms of high dry mass production in the climates found in New Zealand. The temperate rain-fed climate, with only mild winter frosts in most arable districts, could support the growth of an abundance of species. However, the review was not designed to be all-inclusive but ‘nevertheless did consider most non-woody high dry mass species likely to meet the relevant criteria for use as bioenergy crops.’

8.1 The Methodological Tool for Species Selection

The engineering project research aim was to assess the best three New Zealand biomass species in a gasification plant supply model. Our sub-contracted aim for the crop research was to identify three species that are highly suitable to serve this purpose. That ultimate decision will be based on research that includes the species selection phase (with the species short list reported here) and further acquisition of agronomic knowledge on successful culture of the new species, as the basis for selecting the three most suitable species. This information will be applied as inputs to an engineering model on gasification of the biomass.

The review findings should, however, have wider interest and applicability to new energy crops research in other countries. Where there is an urgency to develop renewable fuels, the option of biofuels is likely to be assessed. The first step, screening of biomass species for regional suitability, could easily take a decade but may (as in this case) need to be completed more quickly. This review includes a section on the elements (in addition to a science literature review) of a species selection approach that was able to deliver species selection results in 2 years.

To summarise our 2-year species selection procedure, we:

1. began with a standard international literature review;
2. grouped prospective species into three categories based on growth habit (summer annual, perennial and winter annual);
3. sourced NZ-specific expertise on biomass and weed species, including identification of three well-studied New Zealand crop species to act as a benchmark for each growth habit category;
4. gathered new field data to update findings and fill gaps in New Zealand knowledge;
5. utilised APSIM crop models to simulate dry mass yield of benchmark species in ‘marginal’ site conditions; and
6. used models of the pre-selected candidate species (where they existed) to simulate dry mass yield in marginal conditions to compare to marginal yield of their benchmark species.

The combined use of these elements represents a methodological tool to quantify species screening and ranking. The first two steps shortened the biomass species candidate list from ‘all world species that were reported to have high dry mass yield' to a manageable number for closer examination. The third and fourth steps made use of information particular to New Zealand to further narrow the field to the 15 most promising species. The benchmark species for each growth habit category were the highest yielding arable crop species that also had crop models well calibrated in multiple climatic regions of New Zealand. These were silage maize as the summer annual benchmark, lucerne as the benchmark perennial and winter wheat as the winter annual benchmark.

The final steps involved use of crop models (the Australian APSIM models) to calculate the most relevant 'target yield' to compare candidate species to. This was the simulated dry mass yield of the appropriate benchmark species in the 'marginal' site conditions under which it can still produce an acceptable yield, nominally set at 15 t DM/ha. A species that requires optimal conditions to yield this dry mass would fail the comparison, along with all low dry mass species. When an APSIM crop model also existed for a candidate biomass species then its marginal site yield was also simulated, to allow a direct comparison with the target yield.

These selection procedures will feed into the next stage: agronomic research on crop growth and meeting the year round supply to the fuel plant using a combination of species and biomass storage. No new biomass species came to our attention in the following 18 months that would have met the criteria and whose reported dry mass yield in the climatic range of New Zealand would have ranked it ahead of the species selected (listed in the next section).

8.2 The Selected 'Best' Species for New Zealand

We have identified seven species suitable as gasification feedstock in terms of high yield and adaptation to marginal sites. Any three of these can be used in an engineering supply model for gasification. Two of the benchmark species are among this short list. These are lucerne (*Medicago sativa*) and silage maize (*Zea* mays). The other two suitable arable crops are triticale (*x Triticosecale*) and tickbean (*Vicia faba*). The new or less well-known species identified as the most promising biomass crops in the relevant New Zealand climates were subtropical cultivars of sorghum (*Sorghum bicolor*), Jerusalem artichoke (*Helianthus tuberosus*) and the Mxg clone of Miscanthus (*Miscanthus x giganteus*).

To compare the features of the species we have selected it will be useful to refer back to the Sect. 4 list of the key attributes an ideal New Zealand biofuel crop should possess.

8.2.1 General Features of the Best Biomass Species

Note that three of the 'best' seven species are perennials; these have inherent advantages in terms of sustainability and greenhouse gas minimisation (for both biomass and food crops). Less cultivation lowers CO_2 losses from soil and reduces erosion and nutrient loss to surface waterways.

Biomass species that are somewhat drought resistant but have a good yield response to greater rainfall could be used in ‘marginal’ sites defined as areas where soil water supply is not dependable. That would reserve the most reliable sites for food crops or livestock forage/grazing. The biomass sites would have very high yields in years when they had ample rainfall and could therefore have an overall average dry mass yield that may still prove to be economically viable. This could apply to sorghum in the warmer regions of New Zealand and to Jerusalem artichoke and Miscanthus in many regions.

Special considerations apply to the cooler climate of the lower South Island, although the advantages of using perennial species remain the same. Whether winter annual or summer annual species have a more favourable cropping season depends to some extent on what second crop can be grown to maximise annual biomass. The cooler South Island weather is a disadvantage for many summer annuals, but cereal grains now have high-yielding summer cultivars. This enables both types of rotations: a winter cereal plus a partial short-season crop such as sunflower or a spring cereal followed by a winter legume such as tickbean.

8.2.2 Specific Features of the Best Biomass Species

Jerusalem artichoke. As a new biomass species in New Zealand not all of its features are definitively known. However, its ability to rapidly establish a canopy following spring or early summer planting is a strong point compared to any other perennial crops tested. If each species is rated by the Sect. 4 list of criteria for the ideal biomass crop (repeated at the start of Sect. 8.2), Jerusalem artichoke receives more ticks than any other species. If the European evidence for higher shoot dry mass at higher latitudes is duplicated in New Zealand then Jerusalem artichoke will be a particularly useful species for South Island biomass production.

While shoot dry mass yields are lower than some species, no issues noted to date appear to seriously detract from this species’ potential in the majority of New Zealand (but not the northernmost regions due to lack of chilling of tuber buds). Information is still lacking on the costs and protocols for procedures such as planting and storing tubers.

Miscanthus. The clone Mxg is now planted in research trials and at least three commercial plantings in New Zealand. These have documented the species’ ability to establish and grow well in this country. In terms of the Sect. 4 list of criteria for the ideal biomass crop Mxg satisfies a large number of the criteria and is likely to have a very high dry mass yield. Miscanthus has low nitrogen content in its mass, so it requires less nitrogen fertiliser and its combustion produces less reactive nitrogen.

Some issues to resolve include achieving easy crop establishment using tissue cultured plants. Weed competition has been a major difficulty, particularly in crops being established in the autumn since there are weed species that grow better than Mxg in the mild New Zealand winter climate. Potential issues, such as high moisture content at harvest if regrowth occurs in late winter, can only be resolved once the New Zealand test plantings are old enough.

Lucerne. This perennial benchmark species is well proven for its moderate to high dry mass productivity and adaptability to a wide range of environments, including those that are considered marginal. While the yield is rather sensitive to low temperature and low soil water supply that may also prove to be true of newer species. Another feature of lucerne is past experience using the leaves for higher value feeds; this would leave the stems as a lower-cost energy feedstock. Whole crop lucerne has the same issue as maize silage: a fuel plant will need to compete with its high value as livestock forage. Lucerne ticks many of the criteria of an ideal biomass species, but not low nitrogen content and ease of establishment without irrigation or by minimum tillage. On the other hand, management practices to deal with issues are well developed.

Triticale. This high-yielding cereal grain was selected as the winter annual with the best biomass potential, particularly for use in the cooler parts of New Zealand. Since summer rainfall is much less likely to be limiting in the Southland region the crop land would rarely be 'marginal' for soil water supply. However, there are other yield-limiting factors such as low temperature that could be used to define marginal sites.

Since both winter annual and spring (summer annual) cultivars of triticale produce good yields in the Southland region, there are two cropping scenarios that could use triticale to maximise annual dry mass yield from a site. If used as a winter annual (harvested midsummer) the late summer rainfall may be sufficient for a fast-growing species between the harvest of one winter annual and the planting of the next one, such as sunflower or hemp. This would make use of the solar energy that would be missed between two triticale crops and increase the total biomass yield. Alternatively, with triticale grown as a summer annual the second species would need to be winter hardy and preferably a legume, such as tickbean (*Vicia faba*) or crimson clover (*Trifolium incarnatum*). Triticale ticks a number of criteria of an ideal biomass species, but not the ones to be a perennial, to have low nutrient requirement, easy pest control, and low nitrogen and ash content.

Maize. This benchmark summer annual is the leading biomass crop in Europe, mainly for use in anaerobic digesters for methane. So there are clearly some circumstances where it is justified to grow as biomass, even on regular arable crop land. The use of maize grain for ethanol would be in direct competition with world food supply, but the use of silage maize is only in competition with livestock forage. If subtropical cultivars are grown in a crop rotation and treated differently than forage (fertilised less and harvested prior to seed development) it would increase sustainability relative to a continuous forage maize rotation.

Regarding its production on marginal land, the type of site would differ from sorghum. Maize is too sensitive to water deficit for sites in the higher probability range of drought. On the other hand, sites that are 2 °C too cool for sorghum are still optimal for maize, so sites that are more prone to even cooler seasons may be considered marginal for maize. The same argument as applied to soil water supply in Sect. 8.2.1 may apply to maize regarding cool season risk. Maize ticks the ideal species criteria for high dry mass but not the ones to be a perennial, to have low nutrient requirement, easy pest control, and low nitrogen and ash content.

Sorghum. Subtropical sorghum cultivars showed considerable promise for use in the warmer regions of New Zealand, especially Northland. The trial was irrigated due to an extended drought, so further tests in rain-fed marginal sites are required. The criterion that biomass be produced on 'marginal' sites does create an argument for excluding a summer annual grass like sorghum due to its high nitrogen fertiliser requirement (see Sect. 4.2.3). However, use of a winter legume crop such as tickbean between sorghum crops could address this drawback. Sorghum ticks the ideal species criteria for high dry mass and tolerance of water deficit but not the ones to be a perennial, to have low nutrient requirement, early spring growth, and low nitrogen and ash content.

Species ranking: There is a good chance that both Miscanthus and Jerusalem artichoke will be ranked in the top three biomass species once the agronomic studies characterise the two species' potential in New Zealand. Quantifying the yield of triticale in marginal site conditions also requires added field data or modelling. However, we estimate it will rank in the first four species based on current knowledge. Among the four better-known species the current ranking for use by gasification using the criteria in this review is: (1) maize, (2) lucerne, (3) tickbean and (4) sorghum. For discussion that includes preliminary findings from our 2012 field trials with Jerusalem artichoke see the review article by Kerckhoffs and Renquist (Kerckhoffs and Renquist 2012).

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