Agron. Sustain. Dev. (2013) 33:1–19
DOI 10.1007/s13593-012-0114-9

REVIEW ARTICLE

Biofuel from plant biomass

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Accepted: 29 August 2012 / Published online: 3 October 2012

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 in terms of 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 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. This review identified the most suitable crop species and assessed their production potential for use 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. The data presented have superseded much of the speculative information on the suitability of species for the potential development of a biofuel industry in New Zealand.

Keywords Biomass crops · Energy crops · High dry mass yield · Biofuels · Bioenergy potential · Perennials · LCA · Greenhouse gases · Land use change

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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 (Perlack and Stokes 2011; Boundy et al. 2010) and, in the EU, a study by the Environmental Energy 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 2005) and updated in recent years (e.g. 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 (New Zealand 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 species screening process consisted of a literature review with supporting local assessments to fill the knowledge gaps for unfamiliar species. Conducted from 2008 to 2010, the review identified a ‘short list’ of the six most promising non-woody species for biomass production in ‘marginal’ sites for use as biofuel within the context of New Zealand soil types and climatic range. Greater detail of how this species selection procedure worked was provided in a recent review (Renquist and Kerckhoffs 2012). The details of the final ranking of species 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 the 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 the use of the biomass to replace fossil fuels. The latter aspect was also assessed in a study by Clifton-Brown et al. (2001).

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 2009), in Europe (Amon et al. 2007; Ceotto and Di Candilo 2010) and in the USA Biomass Program and biofuel programmes (Perlack and Stokes 2011; Propheter et al. 2010). Bioenergy programmes are also being set up in the larger developing countries like Brazil and China (Li 2010). Increased research emphasis in the USA is also being placed on the breeding of species to enhance their traits as biomass crops (Simmons et al. 2008). Archontoulis (2011) has noted that whilst 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 classed as ‘weed’ species, are less well described.

2.3.1 Agronomic aspects

Much of the research emphasis on new biomass species has been on the agronomic aspects of their production. Several reports, with a focus on dry mass yield, suggest that 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. 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 Socioeconomic aspects

The potential for the extensive use of land to produce energy crops raises socioeconomic 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 socioeconomic impacts. A large increase in food prices in 2008 was attributed to the use of maize grain and soybeans for fuel in North America. However, a closer analysis showed that there were also price impacts from commodity market speculation involved (Mueller et al. 2011). Another study examined the socioeconomic effects of different facets along the biofuel industry development pathways (Duer and Christensen 2010). These aspects 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. Therefore, it is not surprising that proposals to use land for the purpose of replacing fossil fuels have raised controversies. 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 the 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 the use of the best arable land for biofuel in a world that must grow more food to feed a predicted 10 billion people by 2050 can be challenged as non-sustainable (Blanco-Canqui and Lal 2009; Davis et al. 2009; Ketola and Salmi 2010).

A follow-on issue that has been identified for some cropping situations is *indirect land use change* since the previous use, e.g. tropical rainforest 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 2009). In Brazil, where biofuel production from sugar cane 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 Lemus and Lal (2005). 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 the 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 areas available for energy crops (at the highest scenario of each) are 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 the global scales. 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 that for total food production (De Fraiture and Berndes 2009).

3.4 Nitrogen cycle and use by crops

Nitrogen fertilisation 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 fertilisers (Ceotto 2005). Unfortunately, nitrogen applied to crops as a fertiliser and manure is inefficiently used in most cropping systems. Unused fractions contaminate surface and groundwater resources (Pierce and Rice 1988). Losses occur via denitrification, volatilisation 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 the Earth and includes inorganic reduced and oxidised 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 Candilo 2010). When the crop residues (or whole dedicated energy crop in a rotation) is converted to bioenergy (via combustion, gasification, etc.), the reactive nitrogen is neutralised.

In terms of the relative production of damaging reactive nitrogen, crops with a high yield at a 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 groundwater 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 (one that recycles nutrients).

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; Ketola 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 been 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 once those have been considered, 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 the 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 against 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 aboveground
- 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
- 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. The 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 the less well-studied species. High dry mass was the best criterion for the 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.

The following subsections list species (categorised by crop growth habit) with 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. Since some of the species information from New Zealand is specific to the geographic regions of the country, Fig. 1 provides a reference map (note that low latitudes are in the north end of the country).

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

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 the yield results from 57 different lucerne 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, the highest yields were obtained from lowland soils on alluvium, approx. 15–20 tonnes dry mass per hectare (t DM ha^{-1}). 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 350–550 mm year^{-1}), lucerne had much lower yields (approx. 8–9 t DM ha^{-1}). 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^{-1}, 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.

Agronomy 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^{-1} mm^{-1} of AWC. This was particularly true on light stony soils (Douglas 1986). The recent lucerne research programme by Brown et al. (2003), Brown and Moot (2005) and Teixeira et al. (2007a, b) were on a deep, high water-holding soil and reported yields of 21.3 in year 1, declining after year 3 to 17.5 t DM ha^{-1} 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^{-1} in year 1 and 22.0 t ha^{-1} in 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 DM ha^{-1} in the year it was sown, 17.4 t DM ha^{-1} in year 2 and 14.6 t DM ha^{-1} in year 3. 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.

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.

4.1.2 Giant miscanthus (Miscanthus × giganteus)

Criteria match for dry mass yield The reported dry mass yields have been high to very high in Europe. The most promising genotype is the triploid giant miscanthus (*Miscanthus × giganteus*) (Fig. 2). 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 giant miscanthus to be a consistent high performer with irrigation or summer rainfall: 27 t DM ha^{-1} in Italy (Cosentino et al. 2007) and 28–38 t DM ha^{-1} in Greece (Danalatos et al. 2007). Since giant miscanthus 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, MISCANFOR (Hastings et al. 2009), which simulated a 13-year mean yield for a site in New Zealand (report by A. Hastings, commissioned by Peter

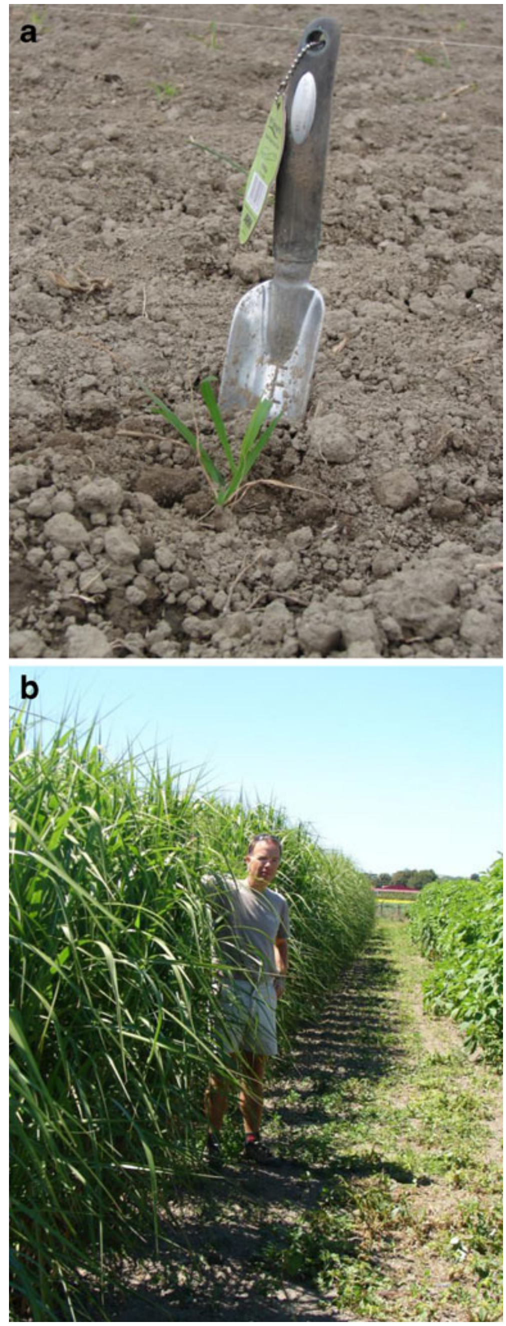

Fig. 2 Giant miscanthus (*Miscanthus × giganteus*). Transplanted as small plantlets with two to four rhizome branches (**a**); height at 12 months, mid-summer to mid-summer (**b**)

Brown). The peak DM in early winter averaged 27 t DM ha^{-1}, whilst late winter mean DM (the time of harvest) was 18.7 t ha^{-1}.

Agronomy European research has compared several genotypes (Clifton-Brown et al. 2001). Findings from several UK trials led to the release of a Production Guide (DEFRA 2001). Mediterranean research has compared several energy crop candidate species and found giant miscanthus to be a consistent high performer, but giant miscanthus 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 whilst the peak dry mass is in early winter, the better time to harvest is after several tonnes of dry mass have been translocated to the rhizome system (along with nutrients to supply early spring growth). The yield at that time is usually 5–10 t DM ha^{-1} below the peak (Clifton-Brown et al. 2004).

Other studies have quantified response to irrigation and nitrogen (Cosentino et al. 2007). Giant 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 have higher nitrogen contents (Ceotto and Di Candilo 2010), and the environmental benefits of giant miscanthus were greater than the 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 the vegetative propagation of the sterile triploid giant miscanthus and the need for modified planting equipment. For a high dry mass yield, giant miscanthus requires rain or soil water into the summer, which is often lacking in the Mediterranean climate. Whilst this would not be an issue in most regions of New Zealand (with >700 mm rainfall, Fig. 2b), 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 regrowth from the top of the plant before harvest is complete. None of these issues appears to negate the potential of this species in many parts of New Zealand, but they will need to be researched.

4.1.3 Jerusalem artichoke (*Helianthus tuberosus*)

Criteria match for dry mass yield Whilst 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 Scandinavian research documented yields from 7 to 20 t DM ha^{-1} (Gunnarson et al. 1985; Wunsche 1985). A trial with multiple shoot harvests in Minnesota (45° latitude) indicated a theoretical yield >25 t DM ha^{-1} (Rawate and Hill 1985). The first New Zealand trials (Fig. 3) had shoot biomass yields in the range of 13–16 t DM ha^{-1} (Kerckhoffs et al. 2011). Much higher shoot yields (>30 t DM ha^{-1}) have been observed in the 2011–2012 trials in Hawke's Bay (unpublished).

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, then 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 >100 stems per square metre compared with 10–20 stems per square metre in the first year. This may require different canopy management if stem population proves to be excessive for optimal use of sunlight.

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. Day length 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.

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 that 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. 3 Jerusalem artichoke (*H. 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**)

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^{-1} and were most often in the 10- to 12-t DM ha^{-1} 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 giant miscanthus in direct comparisons (Heaton et al. 2008).

Agronomy Switchgrass has a low nitrogen requirement and moderately lower water requirement, which is similar to other C4 species such as giant 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 very hardy, grows quickly and spreads easily both by seed and by creeping rhizomes. Dry mass yield under European conditions was <10–12 t DM ha^{-1} in a comparison to giant miscanthus and triticale (Lewandowski and Schmidt 2006).

Agronomy The species is an inferior crop to *Miscanthus* in the climates of northwestern 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).

4.1.6 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 2011) and is also listed as an invasive species in the Pacific Islands.

4.1.7 Cardoon or cynara (Cynara cardunculus)

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 who tolerate the sharp thistle features. It is known for its high biomass yield (>25 t DM ha^{-1}) under favourable conditions (Angelini et al. 2009; Gominho et al. 2011).

Agronomy Recent research into the dynamics of light and nitrogen distribution in canopies (Archontoulis et al. 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.

Issues 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).

4.1.8 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 t DM ha^{-1}) 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 it 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 2012; New Zealand Biosecurity Institute 2009).

4.1.9 Yacon (Smallanthus sonchifolius)

Criteria match for dry mass yield Yacon (Fig. 4) is a tall-growing perennial with very large shoots (over 2 m). Its 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, the fresh mass of shoots was 15.7 t FM ha^{-1} compared with 90 t ha^{-1} 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 ha^{-1}.

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

Fig. 4 Yacon (*S. sonchifolius*). Yacon is grown for its crisp edible root and also has massive shoot growth (but which is quite reduced by root harvest time). Notice there is frost burn of the upper leaves

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.

4.1.10 Cattail or rapu (Typha orientalis)

Criteria match for dry mass yield The New Zealand species of cattail is *Typha orientalis* which has the Maori name rapu. Its common name in North America is cattail and in the UK is bulrush. *T. orientalis* has been studied in relation to the bioremediation of secondary sewage and for biofuel production (Shahbazi 2009). The biology of *T. orientalis* has been detailed in northern New Zealand (Pegman and Ogden 2005), where its annual dry mass productivity was 29.1 t ha^{-1}, with 22.6 t DM ha^{-1} in the shoots.

Agronomy Both due to its very high DM productivity and adaptation to sites not suited for food crops, cattail is an interesting biomass weed to consider cropping. Since many natural wetlands would be excluded from harvest for environmental reasons, commercial production of cattail 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 cattail could make milk production more sustainable whilst 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 ha^{-1} for the two-cut regime compared with 29.7 t ha^{-1} for the one-cut regime (unpublished data). Therefore, cattail 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. Therefore, 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 the commercialisation of cattail 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.

4.1.11 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 ha^{-1} year^{-1} plus an average annual litter fall of 8.9 t ha^{-1} year^{-1}. This was calculated from a 6-year old standing biomass, measured for plants that grew from seed after the site was burned. A goat forage trial in the Canterbury region found the DM yield to be 19.5 t ha^{-1} year^{-1} (Radcliffe 1986). Gorse as biomass crop has a 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 runoff problem.

Agronomy 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.

Issues 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)

Criteria match for dry mass yield Very high DM yields, many in the 25- to 30-t ha^{-1} range, 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 2009–2010 trial at two marginal sites produced maize yields of 29 t DM ha^{-1} in the irrigated site (Fig. 5) and 12.6 t DM ha^{-1} 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 (2007–2008), the mean biomass yield across 44 trials of Pioneer® seed was 22.3 t DM ha^{-1} (B. McCarter, Genetic Technologies Ltd,

Fig. 5 Maize (*Z. mays*). Selection '33M54' is a long-season type and yielded 33.7 t DM ha^{-1} 2 months after this photo in Northland

personal communication). Maize response to nitrogen supply has been characterised in the New Zealand crop model AmaizeN (Li et al. 2006), and the 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; therefore, it is 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 Section 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.

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 ha^{-1} (Steer et al. 1993), and the yield was similar in Oregon, USA, trials (Kiniry et al. 1992); the yield was 11 t DM ha^{-1} in Victoria, Australia (Connor et al. 1985). Dry mass yields were 10.8 t ha^{-1} in research in Turkey (Goksoy et al. 2004) and 12.8–13.9 t ha^{-1} 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^{-1} at the highest plant population density among the several densities that were compared (the overall average yield was 14.4 t DM ha^{-1}). This crop had a very high average growth rate of 173 kg DM ha^{-1} day$-^{1}$ (unpublished data). A 2009–2010 trial at two marginal sites produced sunflower yields of 10.4 and 8.1 t DM ha^{-1} (Fig. 6; Kerckhoffs et al. 2011). The limiting factor was the 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.

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. 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). Another high dry mass factor is the effect of canopy architecture (Archontoulis 2011). Both of these factors are less optimal in sunflower than in very high dry mass species such as cardoon and kenaf (Archontoulis 2011).

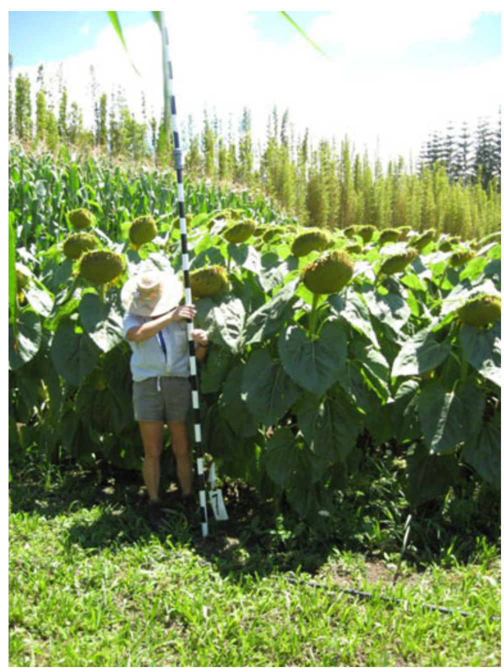

Fig. 6 Sunflower (*H. annum*). Forage sunflower has lower dry mass yield than other species tested and has about 25 % of its dry mass as seeds, which can be lost to birds

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 The dry mass yield of fibre sorghum in the north of Italy was 26.2 t ha^{-1} (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 t DM ha^{-1} from several New Zealand science reports (Cottier 1973; Taylor et al. 1974; Chu and Tillman 1976; Rhodes 1977; Piggot and Farrell 1980, 1984; Causley 1990). However, the mean would be much lower without the results in the reports by Piggot and Farrell (1980) and Piggot and Farrell (1984) who found that 'Sugar Drip' sweet sorghum averaged 25 t DM ha^{-1} in deep loams and well-drained fertile clays and 20 t DM ha^{-1} in dry friable soils in Northland, the warmest part of New Zealand. The best subtropical sorghum cultivar yield in a 2010 Northland trial was 30.3 t DM ha^{-1} (Fig. 7; Kerckhoffs et al. 2011).

Fig. 7 Sorghum (*S. bicolor*). In Northland, the subtropical sorghum × sudan hybrid 'Jumbo' had a 30.3-t DM ha^{-1} yield 2 months after the photo

Agronomy Sorghum is not widely grown in New Zealand, but its use for dairy forage is of current farmer interest. It is generally found to yield lower than silage maize, but to have greater drought tolerance and ability to recover (Singh and Singh 1995). New subtropical cultivars require the 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 the 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 important.

Whilst C4 grass species usually have very high nutrient input requirements, the Northland trial results did not support this. The 'rule of thumb' of the seed company supplying the two best sorghum cultivars is that a 30-t DM ha^{-1} crop would remove over 500 kg ha^{-1} of nitrogen, even if a subtropical species does not produce seed. Our tissue analyses indicated that crop removal was only 240 kg N ha^{-1}.

One feature of sorghum conducive to its use in marginal sites is the 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 the agronomic response and physiology of water use. Another relevant aspect is the effect of sowing rates on biofuel productivity (Wortmann et al. 2010).

Issues The main apparent drawback to the 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 as livestock forage.

Sorghum also has a high nitrogen fertiliser requirement. Whilst tissue analyses from our Northland field trial (Kerckhoffs et al. 2011) indicated that nitrogen uptake in a mature 30-t DM ha^{-1} crop was only 240 kg N ha^{-1}, even this level of nitrogen use is an issue for a biomass crop unless the conversion technology conserves nutrients.

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

Fig. 8 Pearl millet (*Pennisetum glaucum*). The cultivar 'Nutrifeed' yielded 31.2 t DM ha^{-1} 2 months after the photo, similar to subtropical sorghum yields in Northland

Primary Industries and Fisheries 2005). 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^{-1} (Fig. 8; 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, e.g. 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. 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.

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^{-1} in Italy, 19 t DM ha^{-1} in the Netherlands and relatively well on marginal sites (Struik et al. 2000). The highest dry mass yields will probably come from different cultivars than those 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 (14–20 t DM ha^{-1}) makes hemp of interest. 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 one of the authors (RR) 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 ha^{-1} (unpublished data), well below the 15-t DM ha^{-1} 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 ha^{-1} 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.

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 t DM ha^{-1} (Archontoulis 2011). Past research in New Zealand for use as paper pulp showed that in the cooler local climate, the yield was <9 t DM ha^{-1} and the height was <1.7 m (Withers 1973).

Agronomy Canopy architecture findings help explain the high yield potential in the Mediterranean climate (Archontoulis et al. 2011).

Issues Kenaf requires warmer summers than occur in New Zealand. It is also susceptible to *Botrytis* infection and prone to keep growing if soil 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 (also called 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 <15 t ha^{-1} (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^{-1} (Fig. 9; data not yet published).

Fig. 9 Tickbean or broadbean (*V. faba*). These plots yielded >20 t DM ha^{-1} in 2011 due to a warmer than average Hawke's Bay winter

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 the 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.

4.3.2 Winter cereals: wheat (Triticum aestivum), oats (Avena sativa), barley (Hordeum vulgare) and triticale (× 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^{-1} 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 whole crop yield >15 t DM ha^{-1} (de Ruiter 2004; Kerr and Menalda 1976; Stephen et al. 1977). Forage oats yielded 16.9 t DM ha^{-1} 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 ha^{-1} (Kerr and Menalda 1976; Scott and Hines 1991). Triticale whole crop yields can be >20 t DM ha^{-1}, both in the North Island (Scott and Hines 1991) and the southern South Island (Plant & Food Research unpublished trial results for clients). All these yield results are 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). Other research (cited in the previous paragraph) included enhancement of the biomass production of these 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. Among winter annuals, the high dry mass species of interest as biomass crops at higher latitudes are likely to be cereal grains (and perhaps one or two legumes). 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^{-1} 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, which may be high with some cereals. If the economic supply of feedstock for biofuels 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.

5 Rapid species selection approach

The review of literature presented above was the central element in meeting the first 2-year aim of a 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 (Renquist and Shaw 2010). The aim was to obtain a reduced list of high dry mass species with suitable attributes within the 2-year time frame. This species selection approach was detailed in a review that included new local field data and described the use of crop models (Keating et al. 2003) as a tool to estimate dry mass yield in 'marginal' sites and to compare species (Renquist and Kerckhoffs 2012).

Most of the species summarised in Section 4 were dropped from consideration as favoured New Zealand biomass species for reasons cited in the 'Issues' section on each species. The ten remaining species given further consideration are listed in Table 1. The five species that could be grown as summer annuals were also compared in field trials in two regions (Kerckhoffs et al. 2011). The results confirmed that a subtropical cultivar of maize had a very high dry mass; that sorghum and pearl millet were nearly as good and better in drought situations; and that Jerusalem artichoke merited further testing. Subsequent field tests of giant miscanthus support its good potential.

Table 1 Short list of ten promising herbaceous biomass species

Common name	Scientific name
Lucerne	*Medicago sativa*
Harding grass	*Phalaris aquatica*
Miscanthus	*Miscanthus×giganteus*
Jerusalem artichoke	*Helianthus tuberosus*
Maize	*Zea mays*
Sorghum	*Sorghum bicolor*
Pearl millet	*Pennisetum glaucum*
Sunflower	*Helianthus annuus*
Hemp	*Cannabis sativa*
Triticale	*×Triticosecale*

6 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 general and specific attributes of the species deemed best were reviewed elsewhere (Renquist and Kerckhoffs 2012). The result of that ranking procedure is summarised here.

We have identified six species suitable as biofuel feedstock in terms of high yield and adaptation to marginal sites. Among the three better-known species, the current ranking is: (1) maize, (2) lucerne and (3) sorghum. There is a good chance that both giant miscanthus and Jerusalem artichoke will be ranked in the top 3 biomass species once 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, but we estimate that it will rank in the first four species based on current knowledge.

Acknowledgments We thank Eric Lichtfouse and staff for valuable guidance on the manuscript, John de Ruiter for advice on early drafts, Scott Shaw for ideas on the most efficient species screening approach, Glen Cox for analyses using the APSIM model and Brian Rogers for technical assistance. This research was supported by a subcontract within the "*Biomass to Syngas to Liquids*" programme (University of Canterbury, NZ) and by the "*Novel biomass production for sustainable biofuel using new crop cultivars and legumes in a closed-loop nitrogen supply cropping system for use on marginal land*" project (FRST/MAF-Sustainable Land Management Mitigation & Adaptation to Climate Change, NZ).

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