Sustainable use of Miscanthus for biofuel

Robson, Paul; Hastings, Astley; Clifton-Brown, John; McCalmont, Jon

Published in:
Achieving Carbon Negative Bioenergy Systems from Plant Materials

Publication date:
2020

Citation for published version (APA):
Robson, P., Hastings, A., Clifton-Brown, J., & McCalmont, J. (2020). Sustainable use of Miscanthus for biofuel. In C. Saffron (Ed.), *Achieving Carbon Negative Bioenergy Systems from Plant Materials* (Burleigh Dodds Series in Agricultural Science). Burleigh Dodds Science Publishing.

CH15 - Sustainable use of Miscanthus for biofuel

Publisher:	*Burleigh Dodds Science Publishing*
Manuscript ID	BDSP-BK-2018-0219.R1
Manuscript Type:	Book
Date Submitted by the Author:	n/a
Complete List of Authors:	Robson, Paul; Aberystwyth University Hastings, Astley; University of Aberdeen Business School Clifton-Brown, John; Aberystwyth University McAlmont, Jon; University of Exeter College of Life and Environmental Sciences
Keywords:	Miscanthus, bioenergy, biofuel, life cycle assessment, traits

Sustainable use of *Miscanthus* for biofuel

Robson P.R.H. (University of Aberystwyth, UK), Hastings A. (University of Aberdeen, UK), Clifton-Brown J.C. (University of Aberystwyth, UK), McCalmont J.P. (University of Exeter, UK)

Chapter Sections:

Abbreviations: BECCS, Bioenergy with carbon capture and storage; GHG, greenhouse gas; LCA, life cycle assessment; LUC, land-use change

Abstract

Biomass removes carbon dioxide (CO_2) from the atmosphere during growth and if converted to biofuel has the potential to be carbon negative, especially if combined with carbon capture and storage. To achieve ambitious targets for global reductions in greenhouse gas (GHG) emissions biomass crops should generate high yield from minimal input energy while minimising environmental impacts that could make crop production less sustainable. The biomass crop *Miscanthus* has a number of characteristics that make it particularly well suited to sustainably displace fossil fuels. These include C4 photosynthesis combined with cold tolerance, high energy output/input ratios, efficient nutrient recycling and high yield from a perennial crop that requires minimal agronomic input. Life cycle assessment has shown *Miscanthus* generates beneficial GHG and sustainability impacts compared to fossil fuels and other crop systems. The diversity of *Miscanthus* available suggests domestication of this new crop has great potential for use as a biofuel feedstock.

1. Introduction

Highly productive terrestrial plants have the potential to deliver significant amounts of biomass for thermal or chemical conversion to displace fossil fuels and deliver sustainable energy for the future. Of the available candidates for use as bioenergy crops, C4 species have some of the highest potential and recorded productivities of all terrestrial plants (Morison *et al.*, 2000); however, the majority of C4 species are of tropical or subtropical origin and are poorly 'adapted' to growing in cool and temperate climates where C3 species tend to dominate. An exception to this is *Miscanthus*, a perennial rhizomatous grass genus that appears to be more suited to growing under cooler conditions (Jones, 2011). *Miscanthus spp.* have a wide native range covering most of SE. Asia from the Kharbarosk Krai in NE Asian Russia to the tropical Philippines, and from the Himalaya to Taiwan, they have adapted to a variety of different climates and therefore contain considerable diverse genetic potential to create hybrids with improved combinations of traits. Despite this diversity, *Miscanthus* is largely undomesticated and the main commercial type grown is a sterile triploid *M.* × *giganteus* (Greef and Deuter, 1993) thought to arise as a natural hybrid between a diploid *M. sinensis* and a tetraploid *M. sacchariflorus* (Linde-Laursen, 1993). The cultivation of *M.* × *giganteus* has demonstrated good potential as a sustainable biomass crop because it combines a number of useful attributes, some of which will be explored in more detail later, including high dry matter yields, perennial growth, efficient use of nitrogen and water, and good disease resistance. This combination of characteristics has meant *Miscanthus* is of particular interest for growth in temperate regions of Asia, North America and Europe. A large amount of published research has focussed on crop trials within these regions which will therefore be the focus of this review. However, interest in the crop is increasing in other regions of the world such as Africa and many of the considerations around sustainability discussed here will likely be transferrable.

As a perennial crop, *Miscanthus* may be grown continuously from a single cultivation for many years and stands have been harvested for 20 years or more on a yearly cycle. Full harvestable economic yield is usually achieved after 2-3 years. By this time the crop has established sufficient rhizome to produce a dense canopy to maximise seasonal light interception, and consequently yield, with a typical planting density of around 2 plants m^{-2} (Atkinson, 2008). The earliest replicated plot yield trials growing *M.* × *giganteus* in Europe were planted in 1983 in Hornum, Denmark (Jørgensen, 1995) and produced regular autumn yields of 10 to 25 tonnes of dry matter per hectare (Mg DM ha^{-1}) (Lewandowski *et al.*, 2000). A spring harvest allowed improved biomass quality as a solid fuel, particularly lower moisture contents, but at the expense of recoverable biomass with yields up to 30-50% less than autumn yields being reported in European trials (Lewandowski *et al.*, 2000). Commercial interest in *Miscanthus* developed in the USA around 2000 and potential spring harvest yields of 30 t DM ha^{-1} y^{-1} demonstrated the huge potential to produce lignocellulosic biomass from *Miscanthus* in the mid-west USA (Heaton *et al.*, 2008). However, yields of *M.* × *giganteus* showed high inter-annual and inter-site variability, ranging between sites from around 10 to 35 Mg DM ha^{-1} and were inversely correlated with latitude (Lesur *et al.*, 2013). Yield of *Miscanthus* was the most influential factor in its potential for economic return and soil water availability the most crucial input in determining yield (Wang *et al.*, 2012).

In its native Asia *Miscanthus* has a number of uses: the young tips are eaten by humans and the straw is used for thatching, building or animal bedding. *Miscanthus* was used for the conversion of biomass to liquids using gasification and the Fischer-Tropsch process and a pilot plant was operational in Germany from 1998 to 2004 producing bio-diesel (Blades *et al.*, 2005). Other uses of *Miscanthus* explored at this time included direct thermal conversion by combustion and use as a raw material for the paper and pulp industries. The majority of *Miscanthus* currently grown in Europe is used for thermal conversion, i.e. burnt, to generate power or combined heat and power (Baxter *et al.*, 2014) but projects are developing its use across a range of different end uses (Ogunsona *et al.*, 2017; Wagner *et al.*, 2017).

The potential for biomass crop cultivation to compete unfavourably with food production has been discussed widely (Valentine *et al.*, 2012), but one potential benefit of perennial *Miscanthus* is that it may be grown on marginal, poorer quality agricultural land that would otherwise not be economic or suitable for cultivation of food crops. But in considering the potential impact of Miscanthus cultivation it is important to know what area may be practically available for its production. Such considerations may be particularly important in smaller countries where it will be important to know if there is sufficient land available to generate a sufficient quantity of biomass crop for sustainable commercial usage. As an example in the UK Lovett *et al*., (2014) used a ‘constraint mapping’ approach to calculate the potential land available for biomass crops. This GIS mapping approach identified and excluded areas where biomass crops could or should not be grown such as roads, rivers, slopes >15%, areas of cultural heritage and national parks, woodlands, peat soils and natural habitats; these were combined to produce ‘prohibition’ areas at a spatial resolution of 1ha. Also excluded was land graded 1 and 2, the highest quality land, which was regarded as essential for the production of food crops. The less productive land grades 3, 4 and 5 make up the vast majority of the UK agricultural area. What remained was an 8.5 Mha area in the UK that could be considered suitable deployment of these modern energy crops. It is important to consider these significant crop changes carefully as conversion from different land management practices to *Miscanthus* plantation may have either a positive or a negative impact on GHG emissions, physical impacts on radiated energy from albedo change, and further consequences for biodiversity and soil hydrology (Jørgensen *et al.*, 2014). A sensible approach would likely exclude areas of permanent pasture or established woodland (Pogson *et al.*, 2016; Richards *et al.*, 2017).

The 2007 Biomass Strategy (DEFRA, 2007) set a target of 0.35 Mha i.e., less than 5% of the potentially available land identified in Lovett *et al.,* (2014). Modelling studies (Lovett *et al.*, 2009; Hastings *et al.*, 2014) show that the mean yield of *Miscanthus* on grade 3b, 4, and 5 land outside the excluded areas would be around 10 Mg DM ha^{-1} yr^{-1}, and 0.35 Mha could produce up to 70 PJ energy, equivalent to 1.67 Mt of oil or 1.17% of total UK energy. In comparison across the larger areas available in the US with *Miscanthus* yielding 30 Mg ha^{-1}, 12 million ha, or 9.3% of current US cropland, would be sufficient to provide the equivalent of around one-fifth of the current US gasoline use (Heaton *et al.*, 2008). The available areas vary by country, for example, grassland in Ireland accounts for 60% of the agricultural land. This is currently used largely for livestock production but it is possible that future shifts towards diets with less meat and milk or sustainable intensification of extensively managed grasslands, could release significant pasture land for energy crops.

As a source of energy for biofuels, biomass should of course contain more potential energy than is required for growth, harvesting and processing of the crop (i.e. provide an energy output/input ratio significantly greater than 1 (Felten *et al.*, 2013)). Improved sustainability is derived from a number of factors including energy balance, carbon mitigation and environmental impacts. The growth of any crop and perturbation of any living system by removal of biomass will have an effect on factors that impact sustainability. In a study of the cradle to farm gate GHG budget of *Miscanthus* plantations in the UK, Robertson *et al.,* (2017) showed that the main variable was CO_2 rather than other significant GHGs such as methane (CH_4) and nitrous oxide (N_2O). Despite reporting relatively low yields at the study site, these results showed that *Miscanthus* can make a considerable contribution to GHG mitigation in energy production from steam turbines compared with coal and natural gas. However, use in a combined heat and power facility would improve the efficiency of fuel chemical energy conversion to useful energy from 35% to nearer 80%. The importance of specific components of a sustainability assessment are likely to vary between sites because of complex soil/plant/atmosphere interactions and crop management and transport requirements that impact positive and negative effectors of GHG balance. For example, higher local air temperature may achieve a combination of positive and negative impacts.

Positive impacts may occur from higher yield and therefore greater above ground fixed carbon or a drier crop and therefore an increased lower heating value. Negative impacts may include higher soil respiration due to increased soil temperatures and subsequent loss of fixed carbon. The complexity of such interactions necessitates the use of systems models that integrate spatially-explicit climate and soil data together with plant growth and biomass utilisation models to make sustainability predictions at the macro scale. When applied across large areas of land such as Europe, systems models reveal that the sustainability of *Miscanthus* cultivation can be expected to vary dramatically, driven by a complex pattern of changes in yield, soil organic content and carbon intensity from *Miscanthus* cultivation (Figure 1). Such complexities make definitive conclusions difficult, but there are a number of characteristics that can be used to improve the sustainability of *Miscanthus* some of which are discussed below, starting with the energy balance.

2. The energy balance

The balance of energy output to energy input is clearly an important consideration for biomass crops that are used for bioenergy. *Miscanthus* is a low input, fast growing perennial energy grass and as such is an attractive biomass crop (Lewandowski *et al.*, 2003*b*; Harvey, 2007; Heaton *et al.*, 2008, 2010; Zhuang *et al.*, 2013) with energy output/input ratios around ten times that of annual energy crops (Felten *et al.*, 2013). The energy balances for oil seed rape (OSR), maize and *Miscanthus* crops were compared and output/input ratios of 4.7 ± 0.2, 5.5 ± 0.2 and 47.3 ± 2.2 calculated respectively with only the low input *Miscanthus* found to be effectively a CO_2 sink (Felten *et al.*, 2013).

Land is a valuable resource and land cultivated for bioenergy should be utilised efficiently. In terms of energy production intensity, *Miscanthus* biomass produces more net energy per hectare than many other bioenergy crops at around 200-250 GJ ha^{-1} yr^{-1} (Hastings *et al.*, 2012; Felten *et al.*, 2013). These values compare particularly favourably to arable crops, e.g. maize for biogas (98 GJ ha^{-1} yr^{-1}), oil seed rape for biodiesel (25 GJ ha^{-1} yr^{-1}) and wheat and sugar-beet ethanol (7 to 15 GJ ha^{-1} yr^{-1}) (Hastings *et al.*, 2012). Energy production intensity calculated for woody perennials can vary significantly between different areas (Bauen *et al.*, 2010). Tallis *et al.,* (2013) showed that in the right circumstances even old varieties of short-rotation coppice (SRC) willow can exceed 150 GJ ha^{-1} yr^{-1}. A sensible approach is likely to include the strategic planting of combinations of crops across different areas to deliver efficient overall energy production, but adequate consideration should be given to the energy inputs required to achieve different yields and the resulting carbon mitigation. Soil, location and climatic environment will favour specific crops; in a European context this will typically be a choice between woody SRC/short rotation forest (SRF) or *Miscanthus* (Hastings *et al.*, 2014). In addition the equipment required for thermal and chemical processes have to be available to use specific feedstocks of a particular composition.

A high energy ratio and biomass energy density will be important factors in mitigating carbon emissions, and *Miscanthus* has significant potential to reduce fossil fuel CO_2 emission (Clifton-Brown *et al.*, 2004, 2007; Hillier *et al.*, 2009; Hastings *et al.*, 2009). The mitigation of carbon is usually expressed as carbon dioxide equivalent (CO_2-eq.) to allow comparisons across different fuel types and to include the impact of fertilizer use. Carbon mitigation is the sum of fossil fuel carbon emissions displaced minus the carbon cost of growing an energy crop and producing a useable fuel plus any soil carbon sequestration or loss. Depending on soil type, climate and previous land use, soil carbon changes can either add or detract from the overall carbon mitigation. When such factors were modelled across available land in the UK, most of the land could produce *Miscanthus* biomass with a carbon index of 1.12 g CO_2-C equivalent per MJ energy in the furnace. The carbon index value for *Miscanthus* production was substantially lower than coal (33), oil (22), liquefied natural gas (21), Russian gas (20), and North Sea gas (16) (McCalmont *et al.*, 2017). These values were calculated for use of different feedstocks for thermal conversion to electricity but other potential uses of *Miscanthus* are considered in a later section including recent life cycle assessment (LCA) studies.

3. Nutrient use efficiency

Nutrient use efficiency is related to the particular use of the crop. It is important that the crop has the nutrients that are needed to grow efficiently but for biomass crops the harvest is of fixed carbon and therefore many of the nutrients utilised in a growing crop are not required (or are even undesirable) in the harvested product. The composition of the harvested crop such as the carbon content, the form of the carbon and the presence of other compounds determines the ease of conversion. The presence of potential high value bi-products may contribute to the economic sustainability of the conversion process. Thermal conversion of biomass for heat or energy ideally utilises dry biomass with a low water content and a high carbon content. *Miscanthus* has a high C:N ratio (average of 142.6) at spring harvest (Heaton *et al.*, 2009). After senescence when most of the N has been repartitioned to the rhizome and stored for the next growing season and the majority of leaf biomass has fallen to the ground, the remaining long woody stems can be an ideal source of not only carbon for fuel production/burning but also bioplastics and other products. Low N content at harvest time means reduced NOx emissions during burning while the high C content, low levels of easily metabolised sugars and proteins, make the harvested crop a fairly poor food source which contributes to low levels of herbivory and biotic stress.

Lewandowski & Schmidt (2006) compared triticale and reed canary grass to *Miscanthus* and showed far higher N use efficiency in *Miscanthus*. Maximum yields were observed with no fertiliser but with existing soil N at 50 kg N ha^{-1}; higher applications of N fertilisation (above 114 kg N ha^{-1} yr^{-1}) were detrimental to crop performance, particularly where soil water was in short supply. This very low demand for added fertiliser was investigated by (Christian *et* *al.*, 2006) who used ^{15}N isotope enriched nitrogen fertiliser applied at 60 kg N ha^{-1} to study uptake during the establishment phase following planting. Only around 20% of the N taken up by the developing crop had come from the fertiliser, 80% had come from mineralisation of soil organic matter of the former grassland or atmospheric deposition. There is growing evidence that high nutrient efficiency may in part derive from bacterial nitrogen fixation associated with *Miscanthus* (Davis *et al.*, 2010; Dohleman *et al.*, 2012). Nitrogenase activity has been found in both rhizomes and surrounding soil bacteria (Eckert *et al.*, 2001; Miyamoto *et al.*, 2004) with isotope analysis revealing high levels of biologically fixed nitrogen in *Miscanthus* biomass, particularly in the first year of establishment (Keymer and Kent, 2014). One trade-off to this low nitrogen requirement is that emissions and leaching can initially arise following planting into highly fertilised land or grassland killed in preparation for conversion (Christian and Riche, 1998; Behnke *et al.*, 2012; Holder *et al.*, 2018*b*) as *Miscanthus* is unlikely to utilise all the available nutrients in the first year.

The potential for high nitrogen use efficiency means that the need for regular agronomic amendments that would otherwise reduce a favourable energy balance and detract from other sustainability criteria can be largely avoided. Cadoux *et al.*, (2012) reviewed nutrient offtake in mature *Miscanthus* harvests in 27 studies over 10 countries and found a median content of 4.9 g N (kg DM)$^{-1}$ when harvested in the early spring. Given a typical UK offtake of 10 to 15 Mg DM ha^{-1} yr^{-1} the annual export of organic nitrogen from a site in harvest material would range between 49 to 73.5 kg N ha^{-1}. Accounting for an atmospheric N deposition rate of 35-50 kg N ha^{-1} yr^{-1} (Goulding et al. 1998) suggests that *Miscanthus* is unlikely to benefit greatly from inputs of N unless it was being established in very low fertility soils. For example, an optimum application of 100 kg N ha^{-1} was seen to give significant yield benefits on a low fertility sandy loam soil in S. England (Shield *et al.*, 2014). Lewandowski *et al*., (2000) reviewed 19 *Miscanthus* field trials across Europe and reported that there was little response to N fertiliser after the second or third year, though there was some suggestion that early rhizome development may benefit from a low level of application where soils may be low in available N to begin with. Christian *et al.,* (2008) followed a *Miscanthus* crop for 14 years treated with zero, 60 and 120 kg N ha^{-1} yr^{-1} and concluded that there was no yield response from the application of N fertiliser though monitoring of soil fertility and offtake did suggest, in these soils at least, a benefit from additions of phosphate (7 kg P ha^{-1} yr^{-1}) and potassium (100 kg K ha^{-1} yr^{-1}). A large number of studies have been aggregated into a database to demonstrate yield and sustainability across different crops and ecosystems (LeBauer *et al.*, 2018). To avoid negative impacts on sustainability, any increase in yield from fertilizer application would need to be sufficient to offset any associated increased GHG emissions. A life cycle assessment of a mature *Miscanthus* trial showed that yield improvements and the associated increased displacement of fossil fuels associated with different fertilizer application rates were unlikely to be sufficient to offset resulting increased soil N_2O emissions (Roth *et al.*, 2015).

The entire above ground biomass of *Miscanthus* is harvested and therefore the cropped biomass reflects the perennial growth cycle of the plant. This cycle begins with remobilisation of nutrients from below ground rhizome in late spring which are used for early growth, the crop develops a mature canopy and the rhizome is replenished through summer before finally the canopy senesces, typically followed by leaf loss throughout the winter. The latter two processes contribute to the recycling of nutrients so that they are available to the next growth cycle but also negatively impact harvested biomass yield which may decline by up to 30% (Lewandowski and Heinz, 2003). This creates a strong correlation toward the end of the growth year between yield and crop quality with yield declining as some aspects of quality such as moisture and C:N ratio improve. The interaction between yield and quality is of varying importance depending on how the harvested biomass is utilised. A spring harvest of *Miscanthus* greatly improves the suitability of biomass for combustion because the material is usually fully senesced, reducing concentrations of moisture, ash, and alkali metals at the expense of dry matter yield (Lewandowski *et al.*, 2003*a*). An ideal biomass composition for thermal conversion comprises low moisture content, strongly bonded complex molecules such as lignified cell walls and low amounts of N to limit NOx emissions. In addition the presence of compounds that may contribute to the increased ash slagging in boilers, such as silica and potassium, should be low; such compounds lower the slagging temperature and hence reduce thermal efficiency. Heating values of *Miscanthus* biomass have been found to vary due to senescence and/or some other process occurring during the winter period which were not identified but might include nutrient leaching and leaf loss (Lewandowski and Kicherer, 1997). Mos *et al.,* (2013) concluded the change in heating value of *Miscanthus* is likely due to variation in lignin content of crops harvested at different times of the year. The harvest time and associated variation in senescence also impacted the quality and stability of bio-oil made by fast pyrolysis processing of *Miscanthus* biomass with summer harvests producing lower yields of bio-oil. Other harvest dates in September and February produced similar quality bio-oil despite the crop being less-senesced in September than February (Mos *et al.*, 2013). Crop yield declined from September to February suggesting an earlier harvest may be preferable, but harvesting *Miscanthus* early may impact on recycling of nutrients to the rhizome and soil during senescence and leaf-drop that occurs over winter. The resulting depletion of nutrients may in turn affect long-term yields unless these nutrients were replaced, for example using post-processing residue; however, such additional applications would inevitably increase the overall carbon footprint of the crop.

Miscanthus is also used to produce liquid fuels, such as ethanol, which have a different ideal biomass composition requirement. In a study looking at the environmental sustainability of ethanol production from a range of second generation feedstocks, Falano *et al.,* (2014) concluded that the global warming potential of ethanol from *Miscanthus* biomass is more than 80% lower than petrol/ gasoline from fossil sources. A modelling study on biofuel production demonstrated that cellulosic ethanol from *Miscanthus* will have a considerably lower environmental impact than current first generation biofuels (Gabrielle *et al.*, 2014). Conversion of biomass to liquid fuels ideally utilises biomass rich in simple sugars that are easily accessed and energetically favourable for enzymatic or catalytic conversion. Le Ngoc Huyen *et al.,* (2010) showed that harvesting *Miscanthus* at an earlier stage improved saccharification efficiency with alkali pre-treated biomass. Harvesting before full senescence results in more nutrients being harvested which are therefore likely to be above the levels that are replaced by natural annual cycling; however, in a similar approach to that discussed in the preceding paragraph, the digestate can be used as a soil amendment and fertilizer to create a circular nutrient cycle though any resulting impacts on soil trace gas production, such as N_2O, would need to be considered.

Genotypic variation in senescence and therefore composition such as moisture content has been identified across a broad genotypic panel of *Miscanthus* (Robson *et al.*, 2011). Cell wall composition varied between *Miscanthus* growing at different sites and genotypic variation in cell wall composition has been linked to yields of pyrolysis products (Hodgson *et al.*, 2010, 2011). Such studies suggest there is potential to breed for improvements in composition targeted toward conversion efficiency of *Miscanthus* for each end use, but such genotypic improvements may have different impacts across different climatic regions or require specific agronomies.

4. Water use/water use efficiency.

Water is a limiting factor for yield in *Miscanthus,* as in all vegetation, and one major factor that affects the sustainability of bioenergy crops is the use of fresh water for growth. Plants in general use roughly one litre of water to produce between 2-6 grams of biomass, therefore the water use attributed to plant growth for bioenergy may seem very large. However, any land used to grow bioenergy feed-stocks would usually support other plant growth, such as pasture, forest, scrub-land, or other crops if it was not used for bioenergy. So the real question is the difference between the water consumption of the bioenergy feedstock ecosystem and the one it replaces. Evapotranspiration and water use efficiency (WUE), the amount of biomass harvested per unit of water consumed, varied significantly depending on crop and ecosystem (Rockstrom *et al.*, 1999) and therefore the extent of the impact and issues of sustainability will be location specific. As such it is more realistic to focus on the relative performance within a particular environment and how best to increase WUE to obtain “more crop per drop” within sustainable limits of a particular location.

Plant growth is governed by the rate of photosynthesis, a process that consumes a small proportion of the total amount of water that is transpired and produces carbohydrates as one of the products. The efficiency with which water is utilised varies among the three photosynthesis processes used by plants, of which two, known as C3 and C4 are the most common in higher plants. In general, C3 plants, which encompass many grasses, flowering plants and woody trees, use more water per unit biomass than C4 plants. In suitable climates C4 species should exhibit higher efficiencies of radiation, nutrient and water use than C3 species, and hence attain higher productivity. However, C4 photosynthesis is more typical of tropical and subtropical species. In cooler temperate climates most C4 species, for example maize (*Zea mays)*, fail to achieve high productivity due to high thermal requirements for growth and impaired photosynthesis at low temperatures (Miedema *et al.*, 1987; Sage *et al.*, 2010). *Miscanthus* is one of a seemingly small number of C4 species that appear to be well adapted to temperate environments. In a comparison with another temperate C4 grass (*Spartina cynosuroides), Miscanthus* achieved higher WUE, up to 9.1 g kg^{-1}, and retained the theoretical high water use efficiency of C4 species, when grown under temperate conditions (Beale *et al.*, 1999).

Despite highly efficient WUE, producing more biomass may have a significant impact on soil hydrology cycles. Miscanthus used more water across the season (954mm) than comparable plots of maize (611mm) and switchgrass (*Panicum virgatum*) (764mm) at the same location. This resulted from increased latent heat flux (λET) transferring water to the atmosphere and a longer growing season (Hickman *et al.*, 2010), though *Miscanthus* produced more biomass per unit of water used. WUE was very similar between *Miscanthus* at ca. 19 kg ha^{-1} mm^{-1} and maize at ca. 18.6 kg ha^{-1} mm^{-1} and WUE in switchgrass was about half that of maize and *Miscanthus* (Hickman *et al.*, 2010) illustrating the considerable variation that exists even among C4 grass species. Changes in water use may impact ecological functions of land areas and if production of utilisable biomass is an aim then options for high and low biomass crops to limit impacts in hydrologically sensitive areas may be required. This may include a long season, slow growing *Miscanthus* that combines high WUE, provides soil cover to reduce evaporative loss and competition from hydrologically inefficient C3 species. It should be noted that high water use may be a benefit in some regions prone to flooding. A long season canopy may have additional benefits related to excess rainfall. A recent study measured evapotranspiration by eddy covariance in a *Miscanthus* plantation and found it was higher than expected during winter months. The canopy interception of water by *Miscanthus* was similar to that of mixed deciduous forest in the latter months of the year, suggesting the potential for flooding may be reduced by lessening soil water recharge by rainfall (Holder *et al.*, 2018*a*).

Whatever the relative merits of high and low biomass crops, it is likely that a requirement will be for the biomass to be produced with high water use efficiency. Malinowska *et al.,* (2017) examined water use efficiency across a broad genotypic range of *Miscanthus* growing in different water treatments and identified that bigger and faster growing plants tended to have lower WUE suggesting the general trend is in opposition to the more desirable interaction. However, against this trend there were individuals that produced high biomass under control treatments and high WUE under the different water treatments, although the absolute values achieved would need to be confirmed by larger scale field trials. The same study also identified the climatic regions associated with high WUE in *Miscanthus* suggesting where favourable phenotypes might be found and further accessions could be collected with the unusual but highly desirable link between high biomass production and high WUE (Malinowska *et al.*, 2017).

In addition to the water used by the plant to grow, as in any energy system the water used in the conversion of the feedstock into a suitable fuel and then into energy must also be considered. If coal is considered as comparison to biomass fuel, for example, the coal must be mined and washed before use. This uses water and also produces a lot of acidic waste water containing iron and other heavy metals which requires processing before disposal or it will damage water courses and aquifers. Similarly, oil and gas production also produces large quantities of associated subsurface brines which require disposal. Unconventional oil and gas production requires the use of hydrologic fracking, which not only consumes a large quantity of fresh water, but also produces saline and chemical laden brine in the flow-back process which needs careful processing and disposal (Hastings, 2018). Detailed comparisons of water use via different conversion routes have not been produced for *Miscanthus* but such comparisons are likely to be similar among different feedstocks. Water efficiency in the use of the fuel also needs consideration as many thermal power stations do not recover the 54-65% of heat that is not converted into electricity but lose it to the atmosphere, mostly by evaporative cooling in cooling towers. To improve efficiency further any thermal production of electricity should also provide the waste heat for either space heating or industrial processes in a process known as combined heat and power (CHP).

5. Carbon flux

Land disturbance resulting from cultivation for any crop will lead to impacts on the main drivers of soil GHG emissions, i.e. soil oxygen status, microbial diversity, carbon to nitrogen input ratios and hydrological status. Changes of crop type will further perturb the system by changing nutrient availability and mineralisation rates. All these impacts will have a direct bearing on GHG emissions, particularly CO_2 and CH_4 from the decomposition of organic matter and N_2O from nitrification/denitrification processes in the soil. For perennial energy crops primarily aimed at mitigating climate change, such as *Miscanthus*, quantifying these impacts is essential in determining if the crop is a source or sink of GHG, and if it provides useful gains over fossil fuel use. There have been many studies looking at soil carbon fluxes during transitions from conventional crops to *Miscanthus,* many taking advantage of the fact that, being a C4 species as opposed to the C3 crops that are being replaced, soil carbon derived from *Miscanthus* will carry a distinctive isotopic signal (e.g. Clifton-Brown *et al.*, 2007). Among others, Zimmermann et al. (2012) found that in the short term land disturbance resulted in relatively rapid losses of existing C3 soil carbon to the atmosphere. However, the large turnover of root and leaf biomass in *Miscanthus* lead to carbon sequestration rates of 0.6 Mg ha^{-1} yr^{-1} (following arable crops) and 0.9 Mg ha^{-1} yr^{-1} (following grassland), thus, the lost soil carbon loss was replaced within 4 to 5 years. Early work by

(Hansen *et al.*, 2004) found that after a typical *Miscanthus* crop lifetime of around 16 years, 31% of the carbon in the upper soil layers was derived from the *Miscanthus* inputs. This evidence for rapid turnover and replacement of C3 derived soil carbon with C4 has been reported in several other studies, for examples see (Clifton-Brown *et al.*, 2007; Dondini *et al.*, 2009; Zimmermann *et al.*, 2013; Zatta *et al.*, 2014). Previous land-use, and the soil carbon levels associated with it, appear to be key determinants of the levels of carbon sequestration that might be expected following cultivation to *Miscanthus*. Changes from annual crop species to perennial *Miscanthus* production are likely to see increases in soil carbon due the removal of annual soil disturbance and the build-up of large inputs through overwinter leaf drop of around 30% and large inputs from roots (Lewandowski *et al.*, 2000; Zhu *et al.*, 2018). Changes from perennial grassland systems are not so clear cut, with studies more likely to show maintenance of soil carbon stocks at similar levels to starting status (Anderson-Teixeira *et al.*, 2009; Zatta *et al.*, 2014). Recent literature syntheses (Qin *et al.*, 2016; Zang *et al.*, 2018) have confirmed these overall trends with changes to perennial *Miscanthus* from annual cropping showing net sequestration while cultivations into previous grasslands showed no significant change.

Less well studied or reported are the other important greenhouse gases in agriculture, CH_4 and N_2O. While CH_4 is not considered to be an important GHG in temperate cropland, as opposed to during animal production (Snyder *et al.*, 2009), N_2O is a far more significant concern with agriculture being the largest global contributor to atmospheric concentrations. A recent review paper around the sustainability of energy crop production (Whitaker *et al.*, 2018) called for more work on soil N_2O emissions under energy crops and a literature is now beginning to develop, particularly around the critical impact periods during the cropping cycle: cultivations at the beginning and end of crop life and during fertilisation events. Recent work has reported soil N_2O flux at the beginning of *Miscanthus* establishment into grassland (Holder *et al.* 2018) and at the end of the cropping cycle and reversion back to grassland (McCalmont *et al.*, 2018). Both studies revealed significant, short term spikes in soil N_2O emissions driven by soil disturbance associated with crop cultivations; they showed that integrations of these spikes into annual sum estimates added significantly to overall life cycle assessments (LCA) of the GHG costs of crop production. For the land-use conversion period, Holder et al (2018) suggested that directly attributable N_2O costs would add 4.13 Mg ha^{-1} CO_2-eq to a previously calculated LCA carbon cost of the biomass production (Hastings *et al.*, 2017) of 9.49 Mg h^{-1} CO_2-eq (calculated over ten years' production), an increase of 44% over the original estimate which had not considered N_2O emission in its calculation. Similarly, (McCalmont *et al.*, 2018) found that the reversion N_2O costs added around 50% to the overall global warming potential cost of biomass energy production. However, while these figures are significant and need to be considered in GHG accounting for these systems, it should be noted that total CO_2-eq. costs associated with biomass crop production still remain far lower than the equivalent energy produced through more conventional fossil fuels such as coal. McCalmont *et al.,* (2018) calculated that, even including the N_2O cost of reverting back to grassland at the end of crop life, the CO_2 eq. cost of energy produced through *Miscanthus* would be 18 times lower than the equivalent produced through coal. Of course, one key question regarding sustainability of energy crop production and the impact of land-use change remains, and it is the perennial problem of attribution of costs and benefits in LCA studies. If the GHG cost of establishing an energy crop is attributed to the biomass produced then should the GHG cost of its reversion to a more conventional crop also be attributed, or would this be better apportioned to the following crop?

In a modelling exercise for the UK, the relative emissions of a suite of bioenergy crops potentially grown in the UK were analysed for their impact on soil GHG emissions, considering three initial land-use change (LUC) scenarios: from forestry, grassland and arable. These crops included wheat, sugar beet, oil seed rape, *Miscanthus*, short rotation coppice (SRC) willow and poplar and short rotation forestry (SRF) for many species. This analysis showed that where *Miscanthus* yields were the highest, it produced the least GHG emissions. For all conversion from arable emissions were negative, grassland conversions slightly positive and replacing forestry with all crops resulted in significant GHG emissions (Pogson *et al.,* 2016, Richards *et al*., 2017).

6. Life cycle assessment for different end uses

Miscanthus can be used in many pathways for the production of energy. It can be used as a direct fuel for thermal conversion or as a feedstock for conversion to liquid fuels or biogas. *Miscanthus* can also be used as a reinforcing fibre for plastic or cement-based components for either structural engineering use or insulation. The latter structural uses retain the carbon in longer term storage/utilisation, than when biomass is used as a fuel, and therefore have great potential for reducing atmospheric GHG levels. Inherent in energy use is the emission of carbon, with the possible exception of Bioenergy with Carbon Capture and Storage (BECCS) discussed below, and therefore careful consideration must be given to the balance of carbon and environmental impact in comparison to other energy sources across the cycle of use. Such considerations invariably will also include a particular context of economic and/or political requirements. Here we will only consider energy production, although structural and insulation materials can be used to improve energy efficiency. As the two main policy drivers for using bioenergy are to reduce GHG emissions and enhance energy security, each production pathway should be compared using metrics that quantify the potential to achieve these policy objectives and provide a comparison to other energy systems, be they fossil-based or intermittent renewables such as solar, wind, tidal and wave generation.

LCA is commonly used to evaluate the environmental impact of an energy production pathway. This approach defines the boundaries of a process and calculates all of the inputs and outputs to the system, including energy use and waste products, and estimates their impact or cost to the environment. LCAs for various uses of *Miscanthus* have been calculated, from a biomass fuel to a feedstock for producing biogas, biodiesel, methanol and ethanol, to assess if it does indeed reduce emissions compared to alternative fuels within these specific utilisation pathways (Styles and Jones, 2007; Hastings *et al.*, 2012). Of the variables that have been incorporated into a LCA model, the establishment rate of the *Miscanthus* stand and canopy longevity are crucial inputs. The length of time over which energy and equivalent carbon costs accrued at planting are amortised has a significant impact on the overall carbon (and economic) balance. Many models assume a 15 year cycle with 3 years to achieve maximum yield, but *Miscanthus* plantations may be productive for much longer and establish faster and thereby further improve carbon and energy returns.

An early LCA examined the impact of replacing 30% of peat and 10% coal for electricity production in Ireland by co-firing with *Miscanthus*. The reduction in CO_2 emitted was estimated at 1.9 Mt CO_2 eq. yr^{-1} and represented 2.8% of Ireland's 2004 GHG emissions, but was calculated to require just 1.7% of agricultural land area using a conservative estimate of yield (Styles and Jones, 2007). The reduction in CO_2 emissions from incorporating *Miscanthus* into peat or coal electricity generation was so significant that even very low yield estimations continued to generate significant GHG savings, suggesting models have considerable flexibility in the assumptions of benefit. Felten *et al.,* (2013) compared different biomass systems using rapeseed, maize and *Miscanthus*. Compared to equivalent fossil fuel-related energy supply, the potential reduction in CO_2-equivalents ranged between 30-76% for electrical energy from maize biomass, 29-82% for biodiesel from rapeseed, and 96-117% for *Miscanthus* chips. Interestingly the authors concluded that, in their study, CO_2-neutrality was only reached by the *Miscanthus* cropping system and was related to an additional credit from carbon sequestration in soil during the cultivation period; thus, this cropping system acted as a CO_2-sink (Felten *et al.*, 2013). A later paper (Robertson *et al.*, 2017) further concluded that *Miscanthus* cropping could be carbon neutral (incorporating soil N_2O emissions as well as CO_2) even without net carbon sequestration to the soil.

The consideration of GHG emissions should not focus solely on comparisons with fossil fuel alternatives that are displaced by the use of biomass crops but should also include consideration of the impacts of the cropping systems that are displaced. Dondini *et al.,* (2009) compared soil carbon across a soil depth profile in an arable to *Miscanthus* conversion and showed the total amount of soil organic carbon (SOC) was higher under *Miscanthus* than under the arable crop and that this difference was largely due to the input of new carbon. The *Miscanthus* system gained 25.4 Mg C ha^{-1} across the soil profile and this increase in carbon storage within soil appeared to be largely due to the decrease in soil tillage (Dondini *et al.*, 2009), an important advantage in utilising perennial crops. An estimate of yearly carbon mitigation by *Miscanthus* over 15 years ranged from 5.2 to 7.2 Mg C ha^{-1} yr^{-1} depending on time of harvest (Clifton-Brown *et al.*, 2007). Zatta *et al.*, (2014) studied a grassland-to-*Miscanthus* conversion and showed that after an initial decline in SOC due to soil disturbance resulting from cultivation at planting, SOC levels rapidly recovered due to input of new carbon from *Miscanthus*. In this instance the input of more carbon from *Miscanthus* did not produce a significant increase in SOC and the authors suggested the additional carbon may have been utilised through increased microbial respiration, so called soil priming, thus illustrating the potential for complex interactions and the need for empirical data to test assumptions used in models.

The GHG emissions including those associated with land use change were calculated comparing bioenergy feedstock and a rotational food production system it displaced (Styles *et al.*, 2015). Only *Miscanthus* and rotational maize offered GHG savings when indirect land-use change (iLUC) impacts were considered and the percentage of displaced production that was directly replaced had a substantial impact on the estimated global warming potential. However, the GHG benefits for rotational maize were offset by impacts on ecosystem services, and of the six bioenergy crop systems investigated, *Miscanthus* was shown to offer the greatest benefits in the provision of ecosystem services (Styles *et al.*, 2015). Tonini *et al.*, (2012) used sensitivity analysis to show that uncertainties around land use change could have a significant impact on LCA results. They compared four conversion pathways (anaerobic digestion, gasification, small-scale CHP, and large-scale co-firing with coal) for ryegrass (*Lolium perenne*), willow (*Salix spp*), and *Miscanthus* and found that only large-scale co-firing of *Miscanthus* and willow offered real GHG savings compared to fossil fuel alternatives. The impacts of land use change and any positive effects could be localized and consideration should be given to where production might be displaced to and the impacts of any further consequential land-use changes thereby incurred. The consequences of land use change and indirect land use change are complex, particularly the latter, and the impacts and values assigned to such change the subject of recent debate and discussion (Muñoz *et al.*, 2014; Jepson and Caldas, 2017).

The production of biogas from biomass has received much attention recently and serves as a good example of the considerations in assessing the potential impacts and possible benefits of deploying *Miscanthus* as a source of biomass for biofuels. *Miscanthus* has been researched as a potential substrate for the production of biogas, particularly in Germany where biogas production has increased significantly in recent years (Kiesel and Lewandowski, 2017; Kiesel *et al.*, 2017*a*). The cultivation of biomass to provide substrate for anaerobic digestion makes up a significant proportion of the environmental impact and GHG cost of biogas (Hijazi *et al.*, 2016). In the mono-digestion of maize (AD with maize alone) it was the cultivation that had the largest environmental impact due to diesel fuel use in agriculture and emissions linked to fertiliser use (Lijó *et al.*, 2014). *Miscanthus* has been researched as a more environmentally sustainable alternative to the use of maize in biogas production. LCA demonstrated biogas production using *Miscanthus*, as compared with Maize, resulted in a reduction across 5 impact categories such as climate change, terrestrial acidification and eutrophication of water (Kiesel *et al.*, 2017*b*). One of the benefits of dedicated perennial *Miscanthus* crops is the ability to be grown on marginal lands where conventional annual crops would not provide an economically useful return. Marginal lands are usually defined as such due to limitations in productivity which may occur for a number of reasons; these can include abiotic stresses such as low water availability or salinity. *Miscanthus* grown on marginal land was tested for biogas production and showed a cost advantage over similar conversions to biogas using maize (Wagner *et al.*, 2019). Overall yields of *Miscanthus* were critical in the competitiveness of gas production per hectare. Potential reductions to yield of growing Miscanthus on marginal land may be offset by the fact that otherwise unutilised uneconomical land is being brought back in to production. Enhancing *Miscanthus'* capacity to tolerate marginal soil conditions through breeding or imaginative valorisation of other potential benefits such as remediating denuded or contaminated soils and incorporating this into long term rotations with food crops may improve economic viability. Cultivation on overworked and nutrient denuded soils may even increase overall productivity of associated food crops as soils improved by using *Miscanthus* as a long term break crop are brought back into conventional food production.

7. Traits and/or Agronomy for improved sustainability

Yield is an important trait for improvement in *Miscanthus,* and biomass crops in general, and provided increased yield is not achieved through energy intensive means then higher yield improves the energy balance and the economics of the crop. Yield is limited by abiotic stress and water availability in particular. Areas of high solar radiation needed to fuel high yields are often associated with low precipitation. Growing *Miscanthus* on marginal land subject to individual or combinations of stress that limit conventional agriculture, as discussed above, generates a highly desirable mix of sustainability criteria, reduces competition with food crops and possibly regenerates land. Therefore, a key requirement for future development of sustainable *Miscanthus* through breeding is to conserve and enhance this tolerance to abiotic stress and increase yields accordingly. Work is beginning to understand and reduce the impact of abiotic stress on *Miscanthus* including the screening of germplasm under single or combinations of different stresses (Ezaki *et al.*, 2008; Jones *et al.*, 2015; Kalinina *et al.*, 2017; Malinowska *et al.*, 2017; Stavridou *et al.*, 2017; van der Weijde *et al.*, 2017; Fonteyne *et al.*, 2018).

Miscanthus is a versatile biomass feedstock and is utilised in a number of ways across many regions of the world. As discussed above, GHG savings need to be calculated against existing technologies and alternative utilisations and the greatest savings and optimum conversion pathways will vary from region to region. This potential complexity was illustrated by a study across five European countries. At all five sites the highest energy savings were achieved by combined heat and power generation via combustion (Meyer *et al.*, 2017). The GHG savings were more complex: the highest savings were achieved by heat and power production in Portugal (42.7 t CO_2-eq ha^{-1} yr^{-1}); however, at other European locations (Sweden, Denmark, Germany, England), bioethanol production gave the highest GHG savings. However, there was some uncertainty over the ability to generate the GHG savings attributed to the use of fermentation residues for heat in bioethanol production which had a significant contribution to the GHG savings in the scenario discussed. The study concluded that the improved GHG savings were primarily associated with increased yield and that composition was of comparatively lower importance but would impact other sustainability characteristics such as emissions (Meyer *et al.*, 2017).

The economic viability, and competitiveness with less sustainable crops, of growing *Miscanthus* on marginal land for biogas-based electricity production has been shown to be limited by yield (Wagner *et al.*, 2019) so improvements in this area will be an important focus for ongoing research. However, there is also potential for manipulating *Miscanthus* cell wall structure and composition to optimise biomass for particular end uses (Slavov *et al.*, 2013). Lignin in particular is regarded as one of the main factors impeding saccharification by enzymatic hydrolysis as it prevents enzymes accessing the hemicellulose and cellulose in plant cell walls (Zeng *et al.*, 2014). Biomass quality parameters depend on the intended technology for conversion; for example, a low lignin content may improve enzymatic conversion whereas the high energy contained within lignin bonds means that a high lignin content is favourable for thermochemical conversion (Welker *et al.*, 2015). In addition to yield and composition improvements, process optimisation has the potential to increase sustainability and economic viability by reducing the energy required across post-harvesting treatments. The development of such improvements is at an early stage because novel *Miscanthus* cultivars and their usage are still relatively new; however, improvements are already being demonstrated. For example, in the production of biogas there was a considerable cost of pre-treatment of biomass for anaerobic digestion but ensiling *Miscanthus* biomass greatly reduced the need for pre-treatment (Mangold *et al.*, 2019). A study of 50 diverse *Miscanthus* genotypes demonstrated that drought tolerance and cell wall composition were only weakly correlated, suggesting that the potential exists for both traits to be improved independently (van der Weijde *et al.*, 2017). Some traits may be highly aliased and act in opposition but, where possible, future domestication and breeding efforts are likely to target the combined improvement of important traits such as biomass yield, cell wall composition and abiotic stress resilience.

A particular challenge is perhaps one of identifying how to domesticate *Miscanthus* quickly enough to maximise the potential global benefits across a short enough time scale to contribute significantly to the fight against climate change. Breeding programmes are well established across several biomass crops and experiments have demonstrated the potential of next generation sequencing to generate markers and speed up breeding cycles using genome wide association studies (Slavov *et al.*, 2014; Davey *et al.*, 2017) and optimised selection indices to test strategies for efficient improvement of multiple traits (Slavov *et al.*, 2019).

8. Summary and future research priorities

Miscanthus often compares favourably in terms of GHG and energy efficiency with not just the fossil fuel alternatives but also other potential cropping systems that may be used for biomass/bioenergy. Towards the aim of achieving carbon negative biofuel, of particular note is the sequestration of carbon into soils associated with these more stable perennial, rhizomatous systems in many studies. The composition of *Miscanthus* biomass may be optimised for different end uses though the environmental and economic sustainability of such end uses varies across different growing regions. Broadly, it may be assumed that because dry biomass with high C:N ratios, and thus excellent conservation of nutrients within the plant/soil system, is better suited to thermal conversion it is these routes that will achieve the highest savings in GHG (Figure 2). This may be further enhanced by the implementation of bioenergy with carbon capture and storage (BECCS) (Kemper, 2015), a technology that has not yet been thoroughly explored in the *Miscanthus* literature but has great potential for achieving carbon negative biofuel. Implementing BECCS from bioenergy crops at large scale faces a number of challenges such as transport of CO_2 and the colocation of marginal lands and carbon storage basins (Turner *et al.*, 2018). Modelling the potential for BECCS highlights the contributions of biomass residues and dedicated biomass crop growth on marginal land and improving yield. Notwithstanding these contributions other sustainability characteristics discussed previously plus the importance of good governance and the need for effective incentives are also significant factors in modelling the potential of this new technology (Vaughan *et al.*, 2018). The implementation of BECCS would see *Miscanthus* capture carbon from the atmosphere as part of its annual cycle of growth, a portion of that carbon would be sequestered in the soil through the perennial flux of photosynthate from the crop and, as part of the thermal conversion process, CO_2 that would be otherwise re-emitted to the atmosphere would be captured and sequestered in long term storage under sea or ground. This GHG removal technology is a key component in possible future emission scenario pathways to limit global warming to 1.5 °C (IPCC, 2018). The technology readiness to implement BECCS is largely at the demonstration phase but the capture, transport and potential storage capacity suggest that this will be an important part of reducing atmospheric CO_2 levels in the future (Royal Society, 2018) and a key contributor to making biomass crop use even more sustainable.

The growth and harvesting of biomass is of particular significance to overall energy balance and there are a number of crop characteristics that contribute to an improved energy ratio. Many of these are exemplified in the current commercial production of *Miscanthus* but the tremendous geographical range over which *Miscanthus* species are present and the ability to generate wide hybrids between diverse species presents a significant opportunity to improve characteristics and deliver high levels of sustainability along with improved yield and composition. There is further potential to enhance tolerance for growth under marginal conditions to reduce competition with food crops and potentially remediate soils. The unusual cold tolerance of *Miscanthus* provides an additional bonus in allowing the potential benefits of water use efficiency associated with C4 crops to be utilised in temperate regions.

At present the cultivation of bioenergy crops is often seen as separate to food crops in potential competition for land. Perhaps more emphasis should be given to the potential to incorporate *Miscanthus* within land-use rotations with food crops. Improvements in genetics and agronomy are attempting to produce *Miscanthus* plantations that produce economic returns in the second growth year making shorter term plantations more economically attractive and a negative GHG balance achievable in fewer perennial cycles. The perennial rhizomatous nature of *Miscanthus*, and associated reductions in soil disturbance over time, gives it the potential to improve degraded soils by increasing soil carbon, organic matter and earthworm diversity (Kahle *et al.*, 2001; Hansen *et al.*, 2004; Felten and Emmerling, 2011). Perhaps in the future *Miscanthus* will be incorporated into land use rotations as a longer term, low intensity break crop providing a range of alternative bio-products, increasing regional fuel security and socio/economic benefits while enhancing ecosystem services.

The focus of this chapter has been to highlight the research that demonstrates *Miscanthus* embodies a range of attributes that make it an ideal sustainable biomass crop for biofuels. Added to this the diversity identified within global collections of *Miscanthus* species represent a wealth of potential for future improvements. Thus far the impact and potential of *Miscanthus* has mostly been demonstrated using a small number of high yielding clones and experiments with diverse genotypes. These experiments have identified improvements in yield, resilience against stress and improved yield quality. Fewer studies report the tremendous potential of hybridisations between diverse *Miscanthus* genotypes. In the space of a few years the focus of research using *Miscanthus* has been on delivering sustainable solutions, the development of underpinning biological knowledge, agronomy, environmental modelling, LCA and on demonstrating the potential of new genotypes. The main question now is can the investment be made to deliver on the potential within *Miscanthus* fast enough to produce the necessary impact.

9. Where to look for further information

There is a video, FAQs and literature available at the *Miscanthus* Breeding site http://www.miscanthusbreeding.org/.

The context and challenges of climate change and sustainable global decarbonisation including the potential contributions of carbon negative biomass crops are discussed in many reviews including two recently published by IPCC (2018) and the Royal Society (2018). There are a number of reviews that discuss the current status of developing bioenergy crops (Clifton-Brown *et al.*, 2019) and *Miscanthus* at commercial scale (Clifton-Brown *et al.*, 2017) plus reviews of the relative costs and benefits of *Miscanthus* cultivation and a general consideration of land availability, land use, land conversion sustainability and competition for land with food crops (Hastings *et al.*, 2009; Fazio and Monti, 2011; Valentine *et al.*, 2012; Holland *et al.*, 2015; McCalmont *et al.*, 2017).

10. Acknowledgements

The authors thank the many colleagues who contributed the information and papers upon which this chapter is based and the authors acknowledge the support of CERES Inc. and Terravesta Ltd. through the GIANTLINK project (LK0863). This chapter was funded by several projects the UK Biotechnology and Biological Sciences Research Council (grant numbers BBS/E/W/10963A01A and BB/CSP1730/1) and the Natural Environment Research Council (grant numbers NERC - NE/M019691/10 and NERC - NE/P019951/1) and UKERC/FFR2/3.

11. References

Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH. 2009. Changes in soil organic carbon under biofuel crops. GCB Bioenergy **1**, 75–96.

Atkinson CJ. 2008. Establishing perennial grass energy crops in the UK: A review of current propagation options for Miscanthus. Biomass and Bioenergy **33**, 752–759.

Bauen AW, Dunnett AJ, Richter GM, Dailey AG, Aylott M, Casella E, Taylor G. 2010. Modelling supply and demand of bioenergy from short rotation coppice and Miscanthus in the UK. Bioresource Technology **101**, 8132–8143.

Baxter XC, Darvell LI, Jones JM, Barraclough T, Yates NE, Shield I. 2014. Miscanthus combustion properties and variations with Miscanthus agronomy. Fuel **117**, 851–869.

Beale C V, Morison JI., Long SP. 1999. Water use efficiency of C4 perennial grasses in a temperate climate. Agricultural and Forest Meteorology **96**, 103–115.

Behnke GD, David MB, Voigt TB. 2012. Greenhouse Gas Emissions, Nitrate Leaching, and Biomass Yields from Production of Miscanthus × giganteus in Illinois, USA. Bioenergy Research **5**, 801–813.

Blades T, Rudloff M, Schulze O. 2005. Sustainable SunFuel from CHOREN's Carbo-V® Process (CHOREN Industries – Freiberg, Germany). ISAF XV. San Diego.

Cadoux S, Riche AB, Yates NE, Machet JM. 2012. Nutrient requirements of Miscanthus x giganteus: Conclusions from a review of published studies. Biomass and Bioenergy **38**, 14–22.

Christian DG, Poulton PR, Riche AB, Yates NE, Todd AD. 2006. The recovery over several seasons of15N-labelled fertilizer applied to Miscanthus x giganteus ranging from 1 to 3 years old. Biomass and Bioenergy **30**, 125–133.

Christian DG, Riche AB. 1998. Nitrate leaching losses under Miscanthus grass planted on a silty clay loam soil. Soil Use and Management **2**, 131–135.

Christian DG, Riche a. B, Yates NE. 2008. Growth, yield and mineral content of Miscanthus×giganteus grown as a biofuel for 14 successive harvests. Industrial Crops and Products **28**, 320–327.

Clifton-Brown JC, Breuer J, Jones MB. 2007. Carbon mitigation by the energy crop, Miscanthus. Global Change Biology **13**, 2296–2307.

Clifton-Brown JC, Harfouche A, Casler MD, Jones HD, Ashman C, Awty-Carroll D, Bastien C, Bopper S. 2019. Breeding progress and preparedness for mass-scale deployment of perennial lignocellulosic biomass crops switchgrass , miscanthus , willow , and poplar. GCB Bioenergy **11**, 118–151.

Clifton-Brown J, Hastings A, Mos M, *et al.* 2017. Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids. GCB Bioenergy **9**, 6–17.

Clifton-Brown JC, Stampfl PF, Jones MB. 2004. Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Global Change Biology **10**, 509–518.

Davey CL, Robson P, Hawkins S, Farrar K, Clifton-Brown JC, Donnison IS, Slavov GT. 2017. Genetic relationships between spring emergence, canopy phenology, and biomass yield increase the accuracy of genomic prediction in Miscanthus. Journal of Experimental Botany **68**, 5093–5102.

Davis SC, Parton WJ, Dohleman FG, Smith CM, Del Grosso S, Kent AD, DeLucia EH. 2010. Comparative biogeochemical cycles of bioenergy crops reveal nitrogen-fixation and low greenhouse gas emissions in a Miscanthus × giganteus agro-ecosystem. Ecosystems **13**, 144–156.

DEFRA. 2007. Department of Food and Rural Affairs (DEFRA) UK biomass strategy. Available at: http://www.globalbioenergy.org/uploads/media/0705_Defra_-_UK_Biomass_Strategy_01.pdf (accessed 17 October 2018).

Dohleman FG, Heaton EA, Arundale RA, Long SP. 2012. Seasonal dynamics of above- and below-ground biomass and nitrogen partitioning in Miscanthus × giganteus and Panicum virgatum across three growing seasons. GCB Bioenergy **4**, 534–544.

Dondini M, Van Groenigen K-J, Del Galdo I, Jones MB. 2009. Carbon sequestration under Miscanthus: a study of 13C distribution in soil aggregates. GCB Bioenergy **1**, 321–330.

Eckert B, Weber OB, Kirchhof G, Halbritter A, Stoffels M, Hartmann A. 2001. Azospirillum doebereinerae sp. nov., a nitrogen-fixing bacterium associated with the C4-grass Miscanthus. International Journal of Systematic and Evolutionary Microbiology **51**, 17–26.

Ezaki B, Nagao E, Yamamoto Y, Nakashima S, Enomoto T. 2008. Wild plants, Andropogon virginicus L. and Miscanthus sinensis Anders, are tolerant to multiple stresses including aluminum, heavy metals and oxidative stresses. Plant Cell Reports **27**, 951–961.

Falano T, Jeswani HK, Azapagic A. 2014. Assessing the environmental sustainability of ethanol from integrated biorefineries. Biotechnology Journal **9**, 753–765.

Fazio S, Monti A. 2011. Life cycle assessment of different bioenergy production systems including perennial and annual crops. Biomass and Bioenergy **35**, 4868–4878.

Felten D, Emmerling C. 2011. Effects of bioenergy crop cultivation on earthworm communities-A comparative study of perennial (Miscanthus) and annual crops with consideration of graded land-use intensity. Applied Soil Ecology **49**, 167–177.

Felten D, Fröba N, Fries J, Emmerling C. 2013. Energy balances and greenhouse gas-mitigation potentials of bioenergy cropping systems (Miscanthus, rapeseed, and maize) based on farming conditions in Western Germany. Renewable Energy **55**, 160–174.

Fonteyne S, Muylle H, Lootens P, Kerchev P, Van Den Ende W, Staelens A, Reheul D, Roldán-Ruiz I. 2018. Physiological basis of chilling tolerance and early-season growth in miscanthus. Annals of Botany **121**, 281–295.

Gabrielle B, Gagnaire N, Massad RS, Dufossé K, Bessou C. 2014. Environmental assessment of biofuel pathways in Ile de France based on ecosystem modeling. Bioresource Technology **152**, 511–518.

Greef JM, Deuter M. 1993. Syntaxonomy of Miscanthus x giganteus GREEF et DEU. Angewandte Botanik **67**, 87–90.

Hansen EM, Christensen BT, Jensen LS, Kristensen K. 2004. Carbon sequestration in soil beneath long-term Miscanthus plantations as determined by13C abundance. Biomass and Bioenergy **26**, 97–105.

Harvey J. 2007. A versatile solution-growing Miscanthus for bioenergy. Renewable Energy World **10**, 86.

Hastings A. 2018. Bio-energies impact on Natural Capital and Ecosystem Services: A comparison of biomass and coal fuels. Ed. Qin, Z. Mishra, U. Hastings, A. Bioenergy and land use change. Hoboken, NJ: The American Geophysical Union (AGU) and Wiley & Sons.83–97.

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell CP, Stampfl P, Smith P. 2009. Future energy potential of Miscanthus in Europe. GCB Bioenergy **1**, 180–196.

Hastings A, Mos M, Yesufu JA, *et al.* 2017. Economic and Environmental Assessment of Seed and Rhizome Propagated Miscanthus in the UK. Frontiers in Plant Science **8**, 1–16.

Hastings A, Tallis MJ, Casella E, Matthews RW, Henshall PA, Milner S, Smith P, Taylor G. 2014. The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. GCB Bioenergy **6**, 108–122.

Hastings A, Yeluripati J, Hillier J, Smith P. 2012. Chapter 12 – Biofuel crops and greenhouse gasses. Biofuel Crop Production , ed: BP Singh. Wiley Blackwell. ISBN 978-0-470-96304-3,.383–406.

Heaton EA, Dohleman FG, Long SP. 2008. Meeting US biofuel goals with less land: The potential of Miscanthus. Global Change Biology **14**, 2000–2014.

Heaton E a., Dohleman FG, Long SP. 2009. Seasonal nitrogen dynamics of Miscanthus × giganteus and Panicum virgatum. GCB Bioenergy **1**, 297–307.

Heaton EA, Dohleman FG, Miguez AF, *et al.* 2010. Miscanthus. A Promising Biomass Crop. Advances in Botanical Research **56**, 76–137.

Hickman GC, Vanlooche A, Dohleman FG, Bernacchi CJ. 2010. A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. GCB Bioenergy **2**, 157–168.

Hijazi O, Munro S, Zerhusen B, Effenberger M. 2016. Review of life cycle assessment for biogas production in Europe. Renewable and Sustainable Energy Reviews **54**, 1291–1300.

Hillier J, Whittaker C, Dailey G, Aylott M, Casella E, Richter GM, Riche A, Murphy R, Taylor G, Smith P. 2009. Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. GCB Bioenergy **1**, 267–281.

Hodgson EM, Lister SJ, Bridgwater A V., Clifton-Brown J, Donnison IS. 2010. Genotypic and environmentally derived variation in the cell wall composition of Miscanthus in relation to its use as a biomass feedstock. Biomass and Bioenergy **34**, 652–660.

Hodgson EM, Nowakowski DJ, Shield I, Riche A, Bridgwater A V., Clifton-Brown JC, Donnison IS. 2011. Variation in Miscanthus chemical composition and implications for conversion by pyrolysis and thermo-chemical bio-refining for fuels and chemicals. Bioresource Technology **102**, 3411–3418.

Holder AJ, McCalmont JP, McNamara NP, Rowe R, Donnison IS. 2018*a*. Evapotranspiration model comparison and an estimate of field scale Miscanthus canopy precipitation interception. GCB Bioenergy **10**, 353–366.

Holder AJ, McCalmont JP, Rowe R, McNamara NP, Elias D, Donnison IS. 2018*b*. Soil N_2O emissions with different reduced tillage methods during the establishment of Miscanthus in temperate grassland. GCB Bioenergy **11**, 539–549.

Holland RA, Eigenbrod F, Muggeridge A, Brown G, Clarke D, Taylor G. 2015. A synthesis of the ecosystem services impact of second generation bioenergy crop production. Renewable and Sustainable Energy Reviews **46**, 30–40.

IPCC. 2018. Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.). World Meteorological Organization, Geneva, Switzerland, 32 pp..

Jepson W, Caldas M. 2017. “Changing energy systems and land-use change”. Journal of Land Use Science **12**, 405–406.

Jones MB. 2011. C4 species as energy crops. C4 photosynthesis and related CO2 concentrating mechanisms, Advances in photosynthesis and respiration Vol. 32. Dordrecht, The Netherlands: Springer,.379–397.

Jones MB, Finnan J, Hodkinson TR. 2015. Morphological and physiological traits for higher biomass production in perennial rhizomatous grasses grown on marginal land. GCB Bioenergy **7**, 375–385.

Jørgensen U. 1995. Low cost and safe establishment of Miscanthus. Chartier P, Beenackers AACM, Grassi G, eds. Biomass for Energy, Environment, Agriculture and Industry. Oxford: Elsevier.541–547.

Jørgensen S V., Cherubini F, Michelsen O. 2014. Biogenic CO_2 fluxes, changes in surface albedo and biodiversity impacts from establishment of a miscanthus plantation. Journal of Environmental Management **146**, 346–354.

Kahle P, Beuch S, Boelcke B, Leinweber P, Schulten HR. 2001. Cropping of Miscanthus in Central Europe: Biomass production and influence on nutrients and soil organic matter. European Journal of Agronomy **15**, 171–184.

Kalinina O, Nunn C, Sanderson R, *et al.* 2017. Extending Miscanthus Cultivation with Novel Germplasm at Six Contrasting Sites. Frontiers in Plant Science **8**, 1–15.

Kemper J. 2015. Biomass and carbon dioxide capture and storage: A review. International Journal of Greenhouse Gas Control **40**, 401–430.

Keymer DP, Kent AD. 2014. Contribution of nitrogen fixation to first year Miscanthus × giganteus. GCB Bioenergy **6**, 577–586.

Kiesel A, Lewandowski I. 2017. Miscanthus as biogas substrate – cutting tolerance and potential for anaerobic digestion. GCB Bioenergy **9**, 153–167.

Kiesel A, Nunn C, Iqbal Y, *et al.* 2017*a*. Site-Specific Management of Miscanthus Genotypes for Combustion and Anaerobic Digestion: A Comparison of Energy Yields. Frontiers in Plant Science **8**, 1–15.

Kiesel A, Wagner M, Lewandowski I. 2017*b*. Environmental performance of miscanthus, switchgrass and maize: Can C4 perennials increase the sustainability of biogas production? Sustainability (Switzerland) **9**, 5.

LeBauer D, Kooper R, Mulrooney P, Rohde S, Wand D, Long SP, Dietze MC. 2018. BETYdb: a yield , trait , and ecosystem service database applied to second-generation bioenergy feedstock production. GCB Bioenergy **10**, 61–71.

Lesur C, Jeuffroy MH, Makowski D, *et al.* 2013. Modeling long-term yield trends of Miscanthus×giganteus using experimental data from across Europe. Field Crops Research **149**, 252–260.

Lewandowski I, Clifton-Brown JC, Andersson B, *et al.* 2003*a*. Environment and Harvest

Time Affects the Combustion Qualities of Miscanthus Genotypes. Agronomy Journal **95**, 1274–1280.

Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W. 2000. Miscanthus : European experience with a novel energy crop. Biomass and Bioenergy **19**, 209–227.

Lewandowski I, Heinz A. 2003. Delayed harvest of miscanthus — influences on biomass quantity and quality and environmental impacts of energy production. European Journal of Agronomy **19**, 45–63.

Lewandowski I, Kicherer A. 1997. Combustion quality of biomass: Practical relevance and experiments to modify the biomass quality of Miscanthus x giganteus. European Journal of Agronomy **6**, 163–177.

Lewandowski I, Schmidt U. 2006. Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agriculture, Ecosystems & Environment **112**, 335–346.

Lewandowski I, Scurlock JMO, Lindvall E, Christou M. 2003*b*. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy **25**, 335–361.

Lijó L, González-García S, Bacenetti J, Fiala M, Feijoo G, Moreira MT. 2014. Assuring the sustainable production of biogas from anaerobic mono-digestion. Journal of Cleaner Production **72**, 23–34.

Linde-Laursen I. 1993. Cytogenetic analysis of *Miscanthus 'Giganteus'*, an interspecific hybrid. Hereditas **119**, 297–300.

Lovett A, Sünnenberg G, Dockerty T. 2014. The availability of land for perennial energy crops in Great Britain. GCB Bioenergy **6**, 99–107.

Lovett AA, Sünnenberg GM, Richter GM, Dailey AG, Riche AB, Karp A. 2009. Land use implications of increased biomass production identified by gis-based suitability and yield mapping for miscanthus in england. Bioenergy Research **2**, 17–28.

Malinowska M, Donnison IS, Robson PRH. 2017. Phenomics analysis of drought responses in Miscanthus collected from different geographical locations. GCB Bioenergy **9**, 78–91.

Mangold A, Lewandowski I, Möhring J, Clifton-Brown J, Krzyżak J, Mos M, Pogrzeba M, Kiesel A. 2019. Harvest date and leaf : stem ratio determine methane hectare yield of miscanthus biomass. GCB Bioenergy, in press DOI: 10.1111/gcbb.12549.

McCalmont JP, Hastings A, McNamara NP, Richter GM, Robson P, Donnison IS, Clifton-Brown J. 2017. Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. GCB Bioenergy **9**, 489–507.

McCalmont JP, Rowe R, Elias D, Whitaker J, McNamara NP, Donnison IS. 2018. Soil nitrous oxide flux following land-use reversion from Miscanthus and SRC willow to perennial ryegrass. **10**, 914–929.

Meyer F, Wagner M, Lewandowski I. 2017. Optimizing GHG emission and energy-saving performance of miscanthus-based value chains. Biomass Conversion and Biorefinery **7**, 139–152.

Miedema P, Post J, Groot P. 1987. The effects of low temperature on seedling growth in maize genotypes. Agricultural Research Reports Wageningen: Pudoc. **926**, pp 124.

Miyamoto T, Kawahara M, Minamisawa K. 2004. Novel Endophytic Nitrogen-Fixing Clostridia from the Grass Miscanthus sinensis as Revealed by Terminal Restriction Fragment Length Polymorphism Analysis Novel Endophytic Nitrogen-Fixing Clostridia from the Grass Miscanthus sinensis as Revealed by Terminal. Applied and Environmental Microbiology **70**, 6580–6586.

Morison JIL, Piedade MTF, Müller E, Long SP, Junk WJ, Jones MB. 2000. Very high productivity of the C4 aquatic grass Echinochloa polystachya in the Amazon floodplain confirmed by net ecosystem CO_2 flux measurements. Oecologia **125**, 400–411.

Mos M, Banks SW, Nowakowski DJ, Robson PRH, Bridgwater AV, Donnison IS. 2013. Impact of Miscanthus x giganteus senescence times on fast pyrolysis bio-oil quality. Bioresource Technology **129**.

Muñoz I, Schmidt JH, Brandão M, Weidema BP. 2014. Avoiding the streetlight effect : Rebuttal to ' Indirect land use change (iLUC) within life cycle assessment (LCA) – scientific robustness and consistency with international standards ' by prof . Dr . Matthias Finkbeiner. , 1–13.

Le Ngoc Huyen T, Rémond C, Dheilly RM, Chabbert B. 2010. Effect of harvesting date on the composition and saccharification of Miscanthus x giganteus. Bioresource Technology **101**, 8224–8231.

Ogunsona EO, Misra M, Mohanty AK. 2017. Sustainable biocomposites from biobased polyamide 6,10 and biocarbon from pyrolyzed miscanthus fibers. Journal of Applied Polymer Science **134**, 44221.

Pogson M, Richards M, Dondini M, Jones EO, Hastings A, Smith P. 2016. ELUM: A spatial modelling tool to predict soil greenhouse gas changes from land conversion to bioenergy in the UK. Environmental Modelling and Software **84**, 458–466.

Qin Z, Dunn JB, Kwon H, Mueller S, Wander MM. 2016. Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. GCB Bioenergy **8**, 66–80.

Richards M, Pogson M, Dondini M, *et al.* 2017. High-resolution spatial modelling of greenhouse gas emissions from land-use change to energy crops in the United Kingdom. GCB Bioenergy **9**, 627–644.

Robertson AD, Whitaker J, Morrison R, Davies CA, Smith P, McNamara NP. 2017. A Miscanthus plantation can be carbon neutral without increasing soil carbon stocks. GCB Bioenergy **9**, 645–661.

Robson P, Mos M, Clifton-Brown J, Donnison I. 2011. Phenotypic Variation in Senescence in Miscanthus: Towards Optimising Biomass Quality and Quantity. BioEnergy Research **5**, 95–105.

Rockstrom J, Gordon L, Folke C, Kalkenmark M, Engwall M. 1999. Linkages Among Water Vapor Flows, Food Production, and Terrestrial Ecosystem Services. Conservation Ecology **3**, 5.

Roth B, Finnan JM, Jones MB, Burke JI, Williams ML. 2015. Are the benefits of yield responses to nitrogen fertilizer application in the bioenergy crop Miscanthus × giganteus offset by increased soil emissions of nitrous oxide? GCB Bioenergy **7**, 145–152.

Sage RF, Kocacinar F, Kubien DS. 2010. Chapter 10 C4 Photosynthesis and Temperature. Raghavendra A., Sage R. (eds) C4 Photosynthesis and Related CO2 Concentrating Mechanisms. Advances in Photosynthesis and Respiration, vol 32. Springer, Dordrecht.161–195.

Shield IF, Barraclough TJP, Riche AB, Yates NE. 2014. The yield and quality response of the energy grass Miscanthus × giganteus to fertiliser applications of nitrogen, potassium and sulphur. Biomass and Bioenergy **68**, 185–194.

Slavov G, Allison G, Bosch M. 2013. Advances in the genetic dissection of plant cell walls: tools and resources available in Miscanthus. Frontiers in Plant Science **4**, 1–21.

Slavov GT, Davey CL, Bosch M, Robson PRH, Donnison IS, Mackay IJ. 2019. Genomic index selection provides a pragmatic framework for setting and refining multi-objective breeding targets in Miscanthus. Annals of Botany **in press**, doi: 10.1093/aob/mcy187.

Slavov GT, Nipper R, Robson P, Farrar K, Allison GG, Bosch M, Clifton-Brown JC, Donnison IS, Jensen E. 2014. Genome-wide association studies and prediction of 17 traits related to phenology, biomass and cell wall composition in the energy grass Miscanthus sinensis. New Phytologist **201**, 1227–1239.

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems and Environment **133**, 247–266.

Society R. 2018. *Greenhouse gas removal. Available at https://royalsociety.org/~/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf (last accessed October 2018)*.

Stavridou E, Hastings A, Webster RJ, Robson PRH. 2017. The impact of soil salinity on the yield, composition and physiology of the bioenergy grass Miscanthus × giganteus. GCB Bioenergy **9**, 92–104.

Styles D, Gibbons J, Williams AP, Dauber J, Stichnothe H, Urban B, Chadwick DR, Jones DL. 2015. Consequential life cycle assessment of biogas, biofuel and biomass energy options within an arable crop rotation. GCB Bioenergy **7**, 1305–1320.

Styles D, Jones MB. 2007. Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass and Bioenergy **31**, 759–772.

Tallis MJ, Casella E, Henshall PA, Aylott MJ, Randle TJ, Morison JIL, Taylor G. 2013. Development and evaluation of ForestGrowth-SRC a process-based model for short rotation coppice yield and spatial supply reveals poplar uses water more efficiently than willow. GCB

Bioenergy **5**, 53–66.

Tonini D, Hamelin L, Wenzel H, Astrup T. 2012. Bioenergy production from perennial energy crops: A consequential LCA of 12 bioenergy scenarios including land use changes. Environmental Science and Technology **46**, 13521–13530.

Turner PA, Mach KJ, Lobell DB, Benson SM, Baik E, Sanchez DL, Field CB. 2018. The global overlap of bioenergy and carbon sequestration potential. Climatic Change **148**, 1–10.

Valentine J, Clifton-Brown J, Hastings A, Robson P, Allison G, Smith P. 2012. Food vs. fuel: The use of land for lignocellulosic 'next generation' energy crops that minimize competition with primary food production. GCB Bioenergy **4**, 1–19.

Vaughan NE, Gough C, Mander S, Littleton EW, Welfle A, Gernaat DEHJ, Van Vuuren DP. 2018. Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. Environmental Research Letters **13**, 044014.

Wagner M, Kiesel A, Hastings A, Iqbal Y, Lewandowski I. 2017. Novel Miscanthus Germplasm-Based Value Chains: A Life Cycle Assessment. Frontiers in Plant Science **8**, 1–18.

Wagner M, Mangold A, Lask J, Petig E, Kiesel A, Wagner M. 2019. Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. GCB Bioenergy **11**, 34–49.

Wang S, Wang S, Hastings A, Pogson M, Smith P. 2012. Economic and greenhouse gas costs of Miscanthus supply chains in the United Kingdom. GCB Bioenergy **4**, 358–363.

van der Weijde T, Huxley LM, Hawkins S, Sembiring EH, Farrar K, Dolstra O, Visser RGF, Trindade LM. 2017. Impact of drought stress on growth and quality of miscanthus for biofuel production. GCB Bioenergy **9**, 770–782.

Welker CM, Balasubramanian VK, Petti C, Rai KM, De Bolt S, Mendu V. 2015. Engineering plant biomass lignin content and composition for biofuels and bioproducts. Energies **8**, 7654–7676.

Whitaker J, Field JL, Bernacchi CJ, *et al.* 2018. Consensus, uncertainties and challenges for perennial bioenergy crops and land use. GCB Bioenergy **10**, 150–164.

Zang H, Blagodatskaya E, Wen Y, Xu X, Dyckmans J, Kuzyakov Y. 2018. Carbon sequestration and turnover in soil under the energy crop Miscanthus: repeated13C natural abundance approach and literature synthesis. GCB Bioenergy **10**, 262–271.

Zatta A, Clifton-Brown J, Robson P, Hastings A, Monti A. 2014. Land use change from C3 grassland to C4 Miscanthus: Effects on soil carbon content and estimated mitigation benefit after six years. GCB Bioenergy **6**, 360–370.

Zeng Y, Zhao S, Yang S, Ding SY. 2014. Lignin plays a negative role in the biochemical process for producing lignocellulosic biofuels. Current Opinion in Biotechnology **27**, 98–45.

Zhu X, Liang C, Masters MD, Kantola IB, H DE. 2018. The impacts of four potential bioenergy crops on soil carbon dynamics as shown by biomarker analyses and DRIFT spectroscopy. GCB Bioenergy **10**, 489–500.

Zhuang Q, Qin Z, Chen M. 2013. Biofuel, land and water: Maize, switchgrass or Miscanthus? Environmental Research Letters **8**, 015020.

Zimmermann J, Dauber J, Jones MB. 2012. Soil carbon sequestration during the establishment phase of Miscanthus × giganteus: A regional-scale study on commercial farms using13C natural abundance. GCB Bioenergy **4**, 453–461.

Zimmermann J, Dondini M, Jones MB. 2013. Assessing the impacts of the establishment of miscanthus on soil organic carbon on two contrasting land-use types in Ireland. European Journal of Soil Science **64**, 747–756.

Figure legends

Figure 1. Output from the MiscanFor Model (Hastings *et al.,* 2009) using the Harmonized World Soil Data (IIASA) and Climate Research Unit 4.2 climate data of the world as input for period 2000-2010. Top panel:- Map of mean harvest yield for the period 2000-2010 in Mg ha^{-1} y^{-1} with a histogram of yields for EU27 + Switzerland. Scale red=0 to green=30. Black area is non-cropland and high organic soils. Middle panel:- Map of Soil Organic Carbon change of *Miscanthus* planted on arable land, green =sequestration, yellow=no change, red= loss, Histogram show SOC change in EU27 in Mg ha^{-1} y^{-1} Black area is non cropland and high organic soils. Bottom Panel:- Map of carbon intensity of *Miscanthus* fuel for combustion in furnace, grown on arable land, scale green= sequester C, turquoise= less than gas(16), yellow=less than oil(22), red=less than coal (33), Black area is non cropland and high organic soils and more than coal (33), histogram shows carbon intensity of crop grown in EU27 on arable land in g CO_2 eq.C MJ^{-1}.

Figure 2. Carbon flow (below) and approximate greenhouse gas balance (above) achievable from different fuel use scenarios including fossil fuel, green or senesced biomass with and without carbon capture and storage (CCS); adapted from Kemper (2015).

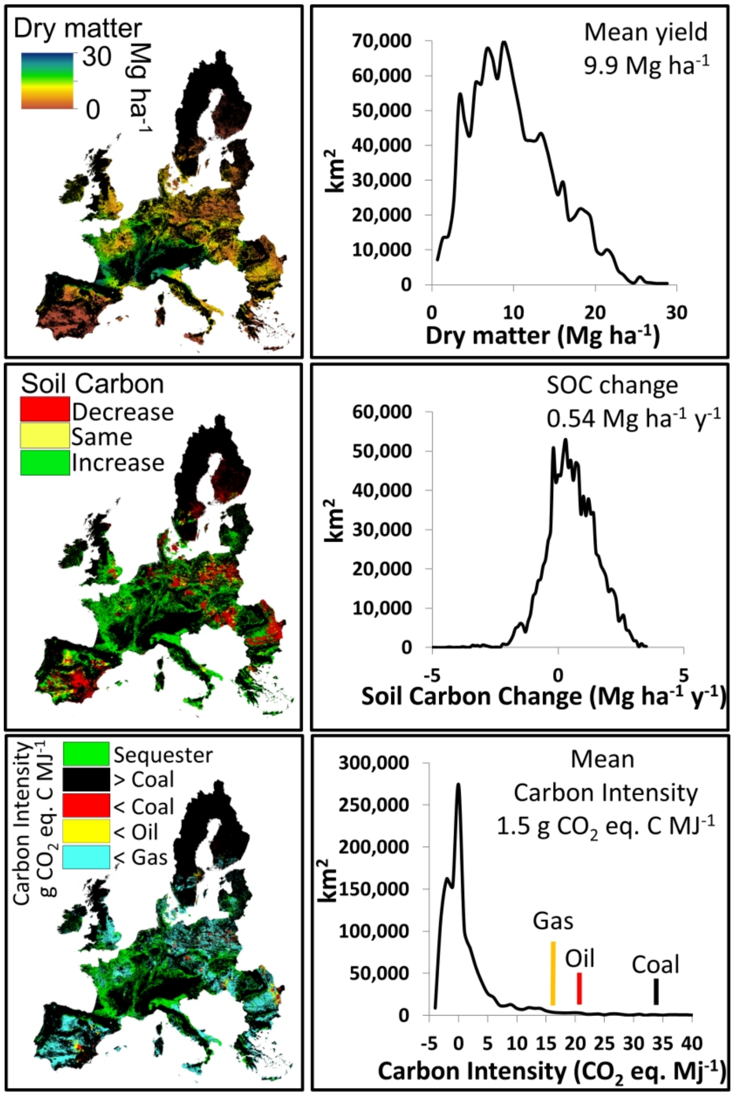

Figure 1. Output from the MiscanFor Model (Hastings et al., 2009) using the Harmonized World Soil Data (IIASA) and Climate Research Unit 4.2 climate data of the world as input for period 2000-2010. Top panel:- Map of mean harvest yield for the period 2000-2010 in Mg ha-1 y-1 with a histogram of yields for EU27 + Switzerland. Scale red=0 to green=30. Black area is non-cropland and high organic soils. Middle panel:- Map of Soil Organic Carbon change of Miscanthus planted on arable land, green =sequestration, yellow=no change, red= loss, Histogram show SOC change in EU27 in Mg ha-1 y-1 Black area is non cropland and high organic soils. Bottom Panel:- Map of carbon intensity of Miscanthus fuel for combustion in furnace, grown on arable land, scale green= sequester C, turquoise= less than gas(16), yellow=less than oil(22), red=less than coal (33), Black area is non cropland and high organic soils and more than coal (33), histogram shows carbon intensity of crop grown in EU27 on arable land in g CO2 eq.C MJ-1.

190x274mm (284 x 284 DPI)

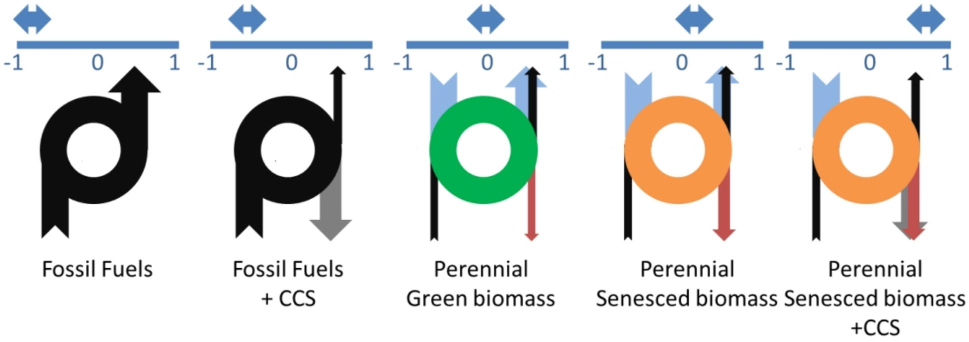

Figure 2. Carbon flow (below) and approximate greenhouse gas balance (above) achievable from different fuel use scenarios including fossil fuel, green or senesced biomass with and without carbon capture and storage (CCS); adapted from Kemper (2015).

259x93mm (150 x 150 DPI)