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Sustainable use of *Miscanthus* for biofuel

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

1

1   **Abstract**

2   Biomass removes carbon dioxide (CO_2) from the atmosphere during growth and if converted

3   to biofuel has the potential to be carbon negative, especially if combined with carbon

4   capture and storage. To achieve ambitious targets for global reductions in greenhouse gas

5   (GHG) emissions biomass crops should generate high yield from minimal input energy while

6   minimising environmental impacts that could make crop production less sustainable. The

7   biomass crop *Miscanthus* has a number of characteristics that make it particularly well

8   suited to sustainably displace fossil fuels. These include C4 photosynthesis combined with

9   cold tolerance, high energy output/input ratios, efficient nutrient recycling and high yield

10   from a perennial crop that requires minimal agronomic input. Life cycle assessment has

11   shown *Miscanthus* generates beneficial GHG and sustainability impacts compared to fossil

12   fuels and other crop systems. The diversity of *Miscanthus* available suggests domestication

13   of this new crop has great potential for use as a biofuel feedstock.

14   **1. Introduction**

15   Highly productive terrestrial plants have the potential to deliver significant amounts of

16   biomass for thermal or chemical conversion to displace fossil fuels and deliver sustainable

17   energy for the future. Of the available candidates for use as bioenergy crops, C4 species

18   have some of the highest potential and recorded productivities of all terrestrial plants

19   (Morison *et al.*, 2000); however, the majority of C4 species are of tropical or subtropical

20   origin and are poorly 'adapted' to growing in cool and temperate climates where C3 species

21   tend to dominate. An exception to this is *Miscanthus*, a perennial rhizomatous grass genus

22   that appears to be more suited to growing under cooler conditions (Jones, 2011).

23   *Miscanthus spp.* have a wide native range covering most of SE. Asia from the Kharbarosk

24   Krai in NE Asian Russia to the tropical Philippines, and from the Himalaya to Taiwan, they

25   have adapted to a variety of different climates and therefore contain considerable diverse

26   genetic potential to create hybrids with improved combinations of traits. Despite this

27   diversity, *Miscanthus* is largely undomesticated and the main commercial type grown is a

28   sterile triploid *M. × giganteus* (Greef and Deuter, 1993) thought to arise as a natural hybrid

29   between a diploid *M. sinensis* and a tetraploid *M. sacchariflorus* (Linde-Laursen, 1993). The

30   cultivation of *M. × giganteus* has demonstrated good potential as a sustainable biomass

31   crop because it combines a number of useful attributes, some of which will be explored in

32   more detail later, including high dry matter yields, perennial growth, efficient use of

33   nitrogen and water, and good disease resistance. This combination of characteristics has

34   meant *Miscanthus* is of particular interest for growth in temperate regions of Asia, North

35   America and Europe. A large amount of published research has focussed on crop trials

36   within these regions which will therefore be the focus of this review. However, interest in

37   the crop is increasing in other regions of the world such as Africa and many of the

38   considerations around sustainability discussed here will likely be transferrable.

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

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

67 The potential for biomass crop cultivation to compete unfavourably with food production
68 has been discussed widely (Valentine *et al.*, 2012), but one potential benefit of perennial
69 *Miscanthus* is that it may be grown on marginal, poorer quality agricultural land that would
70 otherwise not be economic or suitable for cultivation of food crops. But in considering the
71 potential impact of Miscanthus cultivation it is important to know what area may be
72 practically available for its production. Such considerations may be particularly important in
73 smaller countries where it will be important to know if there is sufficient land available to
74 generate a sufficient quantity of biomass crop for sustainable commercial usage. As an
75 example in the UK Lovett *et al.*, (2014) used a 'constraint mapping' approach to calculate
76 the potential land available for biomass crops. This GIS mapping approach identified and
77 excluded areas where biomass crops could or should not be grown such as roads, rivers,
78 slopes >15%, areas of cultural heritage and national parks, woodlands, peat soils and natural

79   habitats; these were combined to produce 'prohibition' areas at a spatial resolution of 1ha.
80   Also excluded was land graded 1 and 2, the highest quality land, which was regarded as
81   essential for the production of food crops. The less productive land grades 3, 4 and 5 make
82   up the vast majority of the UK agricultural area. What remained was an 8.5 Mha area in the
83   UK that could be considered suitable deployment of these modern energy crops. It is
84   important to consider these significant crop changes carefully as conversion from different
85   land management practices to *Miscanthus* plantation may have either a positive or a
86   negative impact on GHG emissions, physical impacts on radiated energy from albedo
87   change, and further consequences for biodiversity and soil hydrology (Jørgensen *et al.*,
88   2014). A sensible approach would likely exclude areas of permanent pasture or established
89   woodland (Pogson *et al.*, 2016; Richards *et al.*, 2017).

90   The 2007 Biomass Strategy (DEFRA, 2007) set a target of 0.35 Mha i.e., less than 5% of the
91   potentially available land identified in Lovett *et al.,* (2014). Modelling studies (Lovett *et al.*,
92   2009; Hastings *et al.*, 2014) show that the mean yield of *Miscanthus* on grade 3b, 4, and 5
93   land outside the excluded areas would be around 10 Mg DM ha^{-1} yr^{-1}, and 0.35 Mha could
94   produce up to 70 PJ energy, equivalent to 1.67 Mt of oil or 1.17% of total UK energy. In
95   comparison across the larger areas available in the US with *Miscanthus* yielding 30 Mg ha^{-1},
96   12 million ha, or 9.3% of current US cropland, would be sufficient to provide the equivalent
97   of around one-fifth of the current US gasoline use (Heaton *et al.*, 2008). The available areas
98   vary by country, for example, grassland in Ireland accounts for 60% of the agricultural land.
99   This is currently used largely for livestock production but it is possible that future shifts
100 towards diets with less meat and milk or sustainable intensification of extensively managed
101 grasslands, could release significant pasture land for energy crops.

102 As a source of energy for biofuels, biomass should of course contain more potential energy
103 than is required for growth, harvesting and processing of the crop (i.e. provide an energy
104 output/input ratio significantly greater than 1 (Felten *et al.*, 2013)). Improved sustainability
105 is derived from a number of factors including energy balance, carbon mitigation and
106 environmental impacts. The growth of any crop and perturbation of any living system by
107 removal of biomass will have an effect on factors that impact sustainability. In a study of the
108 cradle to farm gate GHG budget of *Miscanthus* plantations in the UK, Robertson *et al.*,
109 (2017) showed that the main variable was CO_2 rather than other significant GHGs such as
110 methane (CH_4) and nitrous oxide (N_2O). Despite reporting relatively low yields at the study
111 site, these results showed that *Miscanthus* can make a considerable contribution to GHG
112 mitigation in energy production from steam turbines compared with coal and natural gas.
113 However, use in a combined heat and power facility would improve the efficiency of fuel
114 chemical energy conversion to useful energy from 35% to nearer 80%. The importance of
115 specific components of a sustainability assessment are likely to vary between sites because
116 of complex soil/plant/atmosphere interactions and crop management and transport
117 requirements that impact positive and negative effectors of GHG balance. For example,
118 higher local air temperature may achieve a combination of positive and negative impacts.

4

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

131

132   **2. The energy balance**

133   The balance of energy output to energy input is clearly an important consideration for
134   biomass crops that are used for bioenergy. *Miscanthus* is a low input, fast growing perennial
135   energy grass and as such is an attractive biomass crop (Lewandowski *et al.*, 2003*b*; Harvey,
136   2007; Heaton *et al.*, 2008, 2010; Zhuang *et al.*, 2013) with energy output/input ratios around
137   ten times that of annual energy crops (Felten *et al.*, 2013). The energy balances for oil seed
138   rape (OSR), maize and *Miscanthus* crops were compared and output/input ratios of 4.7 ±
139   0.2, 5.5 ± 0.2 and 47.3 ± 2.2 calculated respectively with only the low input *Miscanthus*
140   found to be effectively a CO_2 sink (Felten *et al.*, 2013).

141   Land is a valuable resource and land cultivated for bioenergy should be utilised efficiently. In
142   terms of energy production intensity, *Miscanthus* biomass produces more net energy per
143   hectare than many other bioenergy crops at around 200-250 GJ ha^{-1} yr^{-1} (Hastings *et al.*,
144   2012; Felten *et al.*, 2013). These values compare particularly favourably to arable crops, e.g.
145   maize for biogas (98 GJ ha^{-1} yr^{-1}), oil seed rape for biodiesel (25 GJ ha^{-1} yr^{-1}) and wheat and
146   sugar-beet ethanol (7 to 15 GJ ha^{-1} yr^{-1}) (Hastings *et al.*, 2012). Energy production intensity
147   calculated for woody perennials can vary significantly between different areas (Bauen *et al.*,
148   2010). Tallis *et al.,* (2013) showed that in the right circumstances even old varieties of short-
149   rotation coppice (SRC) willow can exceed 150 GJ ha^{-1} yr^{-1}. A sensible approach is likely to
150   include the strategic planting of combinations of crops across different areas to deliver
151   efficient overall energy production, but adequate consideration should be given to the
152   energy inputs required to achieve different yields and the resulting carbon mitigation. Soil,
153   location and climatic environment will favour specific crops; in a European context this will
154   typically be a choice between woody SRC/short rotation forest (SRF) or *Miscanthus*
155   (Hastings *et al.*, 2014). In addition the equipment required for thermal and chemical
156   processes have to be available to use specific feedstocks of a particular composition.

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

173

3. Nutrient use efficiency

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

191 Lewandowski & Schmidt (2006) compared triticale and reed canary grass to *Miscanthus* and
192 showed far higher N use efficiency in *Miscanthus*. Maximum yields were observed with no
193 fertiliser but with existing soil N at 50 kg N ha^{-1}; higher applications of N fertilisation (above
194 114 kg N ha^{-1} yr^{-1}) were detrimental to crop performance, particularly where soil water was
195 in short supply. This very low demand for added fertiliser was investigated by (Christian *et*

196   *al.*, 2006) who used ^{15}N isotope enriched nitrogen fertiliser applied at 60 kg N ha^{-1} to study
197   uptake during the establishment phase following planting. Only around 20% of the N taken
198   up by the developing crop had come from the fertiliser, 80% had come from mineralisation
199   of soil organic matter of the former grassland or atmospheric deposition. There is growing
200   evidence that high nutrient efficiency may in part derive from bacterial nitrogen fixation
201   associated with *Miscanthus* (Davis *et al.*, 2010; Dohleman *et al.*, 2012). Nitrogenase activity
202   has been found in both rhizomes and surrounding soil bacteria (Eckert *et al.*, 2001;
203   Miyamoto *et al.*, 2004) with isotope analysis revealing high levels of biologically fixed
204   nitrogen in *Miscanthus* biomass, particularly in the first year of establishment (Keymer and
205   Kent, 2014). One trade-off to this low nitrogen requirement is that emissions and leaching
206   can initially arise following planting into highly fertilised land or grassland killed in
207   preparation for conversion (Christian and Riche, 1998; Behnke *et al.*, 2012; Holder *et al.*,
208   2018*b*) as *Miscanthus* is unlikely to utilise all the available nutrients in the first year.

209   The potential for high nitrogen use efficiency means that the need for regular agronomic
210   amendments that would otherwise reduce a favourable energy balance and detract from
211   other sustainability criteria can be largely avoided. Cadoux *et al.*, (2012) reviewed nutrient
212   offtake in mature *Miscanthus* harvests in 27 studies over 10 countries and found a median
213   content of 4.9 g N (kg DM)$^{-1}$ when harvested in the early spring. Given a typical UK offtake of
214   10 to 15 Mg DM ha^{-1} yr^{-1} the annual export of organic nitrogen from a site in harvest
215   material would range between 49 to 73.5 kg N ha^{-1}. Accounting for an atmospheric N
216   deposition rate of 35-50 kg N ha^{-1} yr^{-1} (Goulding et al. 1998) suggests that *Miscanthus* is
217   unlikely to benefit greatly from inputs of N unless it was being established in very low
218   fertility soils. For example, an optimum application of 100 kg N ha^{-1} was seen to give
219   significant yield benefits on a low fertility sandy loam soil in S. England (Shield *et al.*, 2014).
220   Lewandowski *et al.*, (2000) reviewed 19 *Miscanthus* field trials across Europe and reported
221   that there was little response to N fertiliser after the second or third year, though there was
222   some suggestion that early rhizome development may benefit from a low level of
223   application where soils may be low in available N to begin with. Christian *et al.,* (2008)
224   followed a *Miscanthus* crop for 14 years treated with zero, 60 and 120 kg N ha^{-1} yr^{-1} and
225   concluded that there was no yield response from the application of N fertiliser though
226   monitoring of soil fertility and offtake did suggest, in these soils at least, a benefit from
227   additions of phosphate (7 kg P ha^{-1} yr^{-1}) and potassium (100 kg K ha^{-1} yr^{-1}). A large number of
228   studies have been aggregated into a database to demonstrate yield and sustainability across
229   different crops and ecosystems (LeBauer *et al.*, 2018). To avoid negative impacts on
230   sustainability, any increase in yield from fertilizer application would need to be sufficient to
231   offset any associated increased GHG emissions. A life cycle assessment of a mature
232   *Miscanthus* trial showed that yield improvements and the associated increased
233   displacement of fossil fuels associated with different fertilizer application rates were
234   unlikely to be sufficient to offset resulting increased soil N$_2$O emissions (Roth *et al.*, 2015).

235   The entire above ground biomass of *Miscanthus* is harvested and therefore the cropped
236   biomass reflects the perennial growth cycle of the plant. This cycle begins with
237   remobilisation of nutrients from below ground rhizome in late spring which are used for
238   early growth, the crop develops a mature canopy and the rhizome is replenished through
239   summer before finally the canopy senesces, typically followed by leaf loss throughout the
240   winter. The latter two processes contribute to the recycling of nutrients so that they are
241   available to the next growth cycle but also negatively impact harvested biomass yield which
242   may decline by up to 30% (Lewandowski and Heinz, 2003). This creates a strong correlation
243   toward the end of the growth year between yield and crop quality with yield declining as
244   some aspects of quality such as moisture and C:N ratio improve. The interaction between
245   yield and quality is of varying importance depending on how the harvested biomass is
246   utilised. A spring harvest of *Miscanthus* greatly improves the suitability of biomass for
247   combustion because the material is usually fully senesced, reducing concentrations of
248   moisture, ash, and alkali metals at the expense of dry matter yield (Lewandowski *et al.*,
249   2003*a*). An ideal biomass composition for thermal conversion comprises low moisture
250   content, strongly bonded complex molecules such as lignified cell walls and low amounts of
251   N to limit NOx emissions. In addition the presence of compounds that may contribute to the
252   increased ash slagging in boilers, such as silica and potassium, should be low; such
253   compounds lower the slagging temperature and hence reduce thermal efficiency. Heating
254   values of *Miscanthus* biomass have been found to vary due to senescence and/or some
255   other process occurring during the winter period which were not identified but might
256   include nutrient leaching and leaf loss (Lewandowski and Kicherer, 1997). Mos *et al.,*
257   (2013) concluded the change in heating value of *Miscanthus* is likely due to variation in
258   lignin content of crops harvested at different times of the year. The harvest time and
259   associated variation in senescence also impacted the quality and stability of bio-oil made by
260   fast pyrolysis processing of *Miscanthus* biomass with summer harvests producing lower
261   yields of bio-oil. Other harvest dates in September and February produced similar quality
262   bio-oil despite the crop being less-senesced in September than February (Mos *et al.*, 2013).
263   Crop yield declined from September to February suggesting an earlier harvest may be
264   preferable, but harvesting *Miscanthus* early may impact on recycling of nutrients to the
265   rhizome and soil during senescence and leaf-drop that occurs over winter. The resulting
266   depletion of nutrients may in turn affect long-term yields unless these nutrients were
267   replaced, for example using post-processing residue; however, such additional applications
268   would inevitably increase the overall carbon footprint of the crop.

269   *Miscanthus* is also used to produce liquid fuels, such as ethanol, which have a different ideal
270   biomass composition requirement. In a study looking at the environmental sustainability of
271   ethanol production from a range of second generation feedstocks, Falano *et al.,* (2014)
272   concluded that the global warming potential of ethanol from *Miscanthus* biomass is more
273   than 80% lower than petrol/ gasoline from fossil sources. A modelling study on biofuel
274   production demonstrated that cellulosic ethanol from *Miscanthus* will have a considerably

275 lower environmental impact than current first generation biofuels (Gabrielle *et al.*, 2014).
276 Conversion of biomass to liquid fuels ideally utilises biomass rich in simple sugars that are
277 easily accessed and energetically favourable for enzymatic or catalytic conversion. Le Ngoc
278 Huyen *et al.,* (2010) showed that harvesting *Miscanthus* at an earlier stage improved
279 saccharification efficiency with alkali pre-treated biomass. Harvesting before full senescence
280 results in more nutrients being harvested which are therefore likely to be above the levels
281 that are replaced by natural annual cycling; however, in a similar approach to that discussed
282 in the preceding paragraph, the digestate can be used as a soil amendment and fertilizer to
283 create a circular nutrient cycle though any resulting impacts on soil trace gas production,
284 such as N_2O, would need to be considered.

285 Genotypic variation in senescence and therefore composition such as moisture content has
286 been identified across a broad genotypic panel of *Miscanthus* (Robson *et al.*, 2011). Cell wall
287 composition varied between *Miscanthus* growing at different sites and genotypic variation
288 in cell wall composition has been linked to yields of pyrolysis products (Hodgson *et al.*, 2010,
289 2011). Such studies suggest there is potential to breed for improvements in composition
290 targeted toward conversion efficiency of *Miscanthus* for each end use, but such genotypic
291 improvements may have different impacts across different climatic regions or require
292 specific agronomies.

293

294 **4. Water use/water use efficiency.**

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

308 Plant growth is governed by the rate of photosynthesis, a process that consumes a small
309 proportion of the total amount of water that is transpired and produces carbohydrates as
310 one of the products. The efficiency with which water is utilised varies among the three
311 photosynthesis processes used by plants, of which two, known as C3 and C4 are the most
312 common in higher plants. In general, C3 plants, which encompass many grasses, flowering

313   plants and woody trees, use more water per unit biomass than C4 plants. In suitable
314   climates C4 species should exhibit higher efficiencies of radiation, nutrient and water use
315   than C3 species, and hence attain higher productivity. However, C4 photosynthesis is more
316   typical of tropical and subtropical species. In cooler temperate climates most C4 species, for
317   example maize (*Zea mays)*, fail to achieve high productivity due to high thermal
318   requirements for growth and impaired photosynthesis at low temperatures (Miedema *et al.*,
319   1987; Sage *et al.*, 2010). *Miscanthus* is one of a seemingly small number of C4 species that
320   appear to be well adapted to temperate environments. In a comparison with another
321   temperate C4 grass (*Spartina cynosuroides), Miscanthus* achieved higher WUE, up to 9.1 g
322   kg^{-1}, and retained the theoretical high water use efficiency of C4 species, when grown under
323   temperate conditions (Beale *et al.*, 1999).

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

344   Whatever the relative merits of high and low biomass crops, it is likely that a requirement
345   will be for the biomass to be produced with high water use efficiency. Malinowska *et al.,*
346   (2017) examined water use efficiency across a broad genotypic range of *Miscanthus* growing
347   in different water treatments and identified that bigger and faster growing plants tended to
348   have lower WUE suggesting the general trend is in opposition to the more desirable
349   interaction. However, against this trend there were individuals that produced high biomass
350   under control treatments and high WUE under the different water treatments, although the
351   absolute values achieved would need to be confirmed by larger scale field trials. The same
352   study also identified the climatic regions associated with high WUE in *Miscanthus* suggesting

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353 where favourable phenotypes might be found and further accessions could be collected
354 with the unusual but highly desirable link between high biomass production and high WUE
355 (Malinowska *et al.*, 2017).

356 In addition to the water used by the plant to grow, as in any energy system the water used
357 in the conversion of the feedstock into a suitable fuel and then into energy must also be
358 considered. If coal is considered as comparison to biomass fuel, for example, the coal must
359 be mined and washed before use. This uses water and also produces a lot of acidic waste
360 water containing iron and other heavy metals which requires processing before disposal or
361 it will damage water courses and aquifers. Similarly, oil and gas production also produces
362 large quantities of associated subsurface brines which require disposal. Unconventional oil
363 and gas production requires the use of hydrologic fracking, which not only consumes a large
364 quantity of fresh water, but also produces saline and chemical laden brine in the flow-back
365 process which needs careful processing and disposal (Hastings, 2018). Detailed comparisons
366 of water use via different conversion routes have not been produced for *Miscanthus* but
367 such comparisons are likely to be similar among different feedstocks. Water efficiency in the
368 use of the fuel also needs consideration as many thermal power stations do not recover the
369 54-65% of heat that is not converted into electricity but lose it to the atmosphere, mostly by
370 evaporative cooling in cooling towers. To improve efficiency further any thermal production
371 of electricity should also provide the waste heat for either space heating or industrial
372 processes in a process known as combined heat and power (CHP).

373

5. Carbon flux

375 Land disturbance resulting from cultivation for any crop will lead to impacts on the main
376 drivers of soil GHG emissions, i.e. soil oxygen status, microbial diversity, carbon to nitrogen
377 input ratios and hydrological status. Changes of crop type will further perturb the system by
378 changing nutrient availability and mineralisation rates. All these impacts will have a direct
379 bearing on GHG emissions, particularly CO_2 and CH_4 from the decomposition of organic
380 matter and N_2O from nitrification/denitrification processes in the soil. For perennial energy
381 crops primarily aimed at mitigating climate change, such as *Miscanthus*, quantifying these
382 impacts is essential in determining if the crop is a source or sink of GHG, and if it provides
383 useful gains over fossil fuel use. There have been many studies looking at soil carbon fluxes
384 during transitions from conventional crops to *Miscanthus,* many taking advantage of the
385 fact that, being a C4 species as opposed to the C3 crops that are being replaced, soil carbon
386 derived from *Miscanthus* will carry a distinctive isotopic signal (e.g. Clifton-Brown *et al.*,
387 2007). Among others, Zimmermann et al. (2012) found that in the short term land
388 disturbance resulted in relatively rapid losses of existing C3 soil carbon to the atmosphere.
389 However, the large turnover of root and leaf biomass in *Miscanthus* lead to carbon
390 sequestration rates of 0.6 Mg ha^{-1} yr^{-1} (following arable crops) and 0.9 Mg ha^{-1} yr^{-1} (following
391 grassland), thus, the lost soil carbon loss was replaced within 4 to 5 years. Early work by

392   (Hansen *et al.*, 2004) found that after a typical *Miscanthus* crop lifetime of around 16 years,
393   31% of the carbon in the upper soil layers was derived from the *Miscanthus* inputs. This
394   evidence for rapid turnover and replacement of C3 derived soil carbon with C4 has been
395   reported in several other studies, for examples see (Clifton-Brown *et al.*, 2007; Dondini *et*
396   *al.*, 2009; Zimmermann *et al.*, 2013; Zatta *et al.*, 2014). Previous land-use, and the soil
397   carbon levels associated with it, appear to be key determinants of the levels of carbon
398   sequestration that might be expected following cultivation to *Miscanthus*. Changes from
399   annual crop species to perennial *Miscanthus* production are likely to see increases in soil
400   carbon due the removal of annual soil disturbance and the build-up of large inputs through
401   overwinter leaf drop of around 30% and large inputs from roots (Lewandowski *et al.*, 2000;
402   Zhu *et al.*, 2018). Changes from perennial grassland systems are not so clear cut, with
403   studies more likely to show maintenance of soil carbon stocks at similar levels to starting
404   status (Anderson-Teixeira *et al.*, 2009; Zatta *et al.*, 2014). Recent literature syntheses (Qin *et*
405   *al.*, 2016; Zang *et al.*, 2018) have confirmed these overall trends with changes to perennial
406   *Miscanthus* from annual cropping showing net sequestration while cultivations into previous
407   grasslands showed no significant change.

408   Less well studied or reported are the other important greenhouse gases in agriculture, CH_4
409   and N_2O. While CH_4 is not considered to be an important GHG in temperate cropland, as
410   opposed to during animal production (Snyder *et al.*, 2009), N_2O is a far more significant
411   concern with agriculture being the largest global contributor to atmospheric concentrations.
412   A recent review paper around the sustainability of energy crop production (Whitaker *et al.*,
413   2018) called for more work on soil N_2O emissions under energy crops and a literature is now
414   beginning to develop, particularly around the critical impact periods during the cropping
415   cycle: cultivations at the beginning and end of crop life and during fertilisation events.
416   Recent work has reported soil N_2O flux at the beginning of *Miscanthus* establishment into
417   grassland (Holder *et al.* 2018) and at the end of the cropping cycle and reversion back to
418   grassland (McCalmont *et al.*, 2018). Both studies revealed significant, short term spikes in
419   soil N_2O emissions driven by soil disturbance associated with crop cultivations; they showed
420   that integrations of these spikes into annual sum estimates added significantly to overall life
421   cycle assessments (LCA) of the GHG costs of crop production. For the land-use conversion
422   period, Holder et al (2018) suggested that directly attributable N_2O costs would add 4.13 Mg
423   ha^{-1} CO_2-eq to a previously calculated LCA carbon cost of the biomass production (Hastings
424   *et al.*, 2017) of 9.49 Mg h^{-1} CO_2-eq (calculated over ten years' production), an increase of
425   44% over the original estimate which had not considered N_2O emission in its calculation.
426   Similarly, (McCalmont *et al.*, 2018) found that the reversion N_2O costs added around 50% to
427   the overall global warming potential cost of biomass energy production. However, while
428   these figures are significant and need to be considered in GHG accounting for these
429   systems, it should be noted that total CO_2-eq. costs associated with biomass crop
430   production still remain far lower than the equivalent energy produced through more
431   conventional fossil fuels such as coal. McCalmont *et al.*, (2018) calculated that, even

432 including the N$_2$O cost of reverting back to grassland at the end of crop life, the CO$_2$ eq. cost
433 of energy produced through *Miscanthus* would be 18 times lower than the equivalent
434 produced through coal. Of course, one key question regarding sustainability of energy crop
435 production and the impact of land-use change remains, and it is the perennial problem of
436 attribution of costs and benefits in LCA studies. If the GHG cost of establishing an energy
437 crop is attributed to the biomass produced then should the GHG cost of its reversion to a
438 more conventional crop also be attributed, or would this be better apportioned to the
439 following crop?

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

449

450 **6. Life cycle assessment for different end uses**

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

468 LCA is commonly used to evaluate the environmental impact of an energy production
469 pathway. This approach defines the boundaries of a process and calculates all of the inputs

470   and outputs to the system, including energy use and waste products, and estimates their

471   impact or cost to the environment. LCAs for various uses of *Miscanthus* have been

472   calculated, from a biomass fuel to a feedstock for producing biogas, biodiesel, methanol and

473   ethanol, to assess if it does indeed reduce emissions compared to alternative fuels within

474   these specific utilisation pathways (Styles and Jones, 2007; Hastings *et al.*, 2012). Of the

475   variables that have been incorporated into a LCA model, the establishment rate of the

476   *Miscanthus* stand and canopy longevity are crucial inputs. The length of time over which

477   energy and equivalent carbon costs accrued at planting are amortised has a significant

478   impact on the overall carbon (and economic) balance. Many models assume a 15 year cycle

479   with 3 years to achieve maximum yield, but *Miscanthus* plantations may be productive for

480   much longer and establish faster and thereby further improve carbon and energy returns.

481   An early LCA examined the impact of replacing 30% of peat and 10% coal for electricity

482   production in Ireland by co-firing with *Miscanthus*. The reduction in CO_2 emitted was

483   estimated at 1.9 Mt CO_2 eq. yr^{-1} and represented 2.8% of Ireland's 2004 GHG emissions, but

484   was calculated to require just 1.7% of agricultural land area using a conservative estimate of

485   yield (Styles and Jones, 2007). The reduction in CO_2 emissions from incorporating

486   *Miscanthus* into peat or coal electricity generation was so significant that even very low

487   yield estimations continued to generate significant GHG savings, suggesting models have

488   considerable flexibility in the assumptions of benefit. Felten *et al.,* (2013) compared

489   different biomass systems using rapeseed, maize and *Miscanthus*. Compared to equivalent

490   fossil fuel-related energy supply, the potential reduction in CO_2-equivalents ranged between

491   30-76% for electrical energy from maize biomass, 29-82% for biodiesel from rapeseed, and

492   96-117% for *Miscanthus* chips. Interestingly the authors concluded that, in their study, CO_2-

493   neutrality was only reached by the *Miscanthus* cropping system and was related to an

494   additional credit from carbon sequestration in soil during the cultivation period; thus, this

495   cropping system acted as a CO_2-sink (Felten *et al.*, 2013). A later paper (Robertson *et al.*,

496   2017) further concluded that *Miscanthus* cropping could be carbon neutral (incorporating

497   soil N_2O emissions as well as CO_2) even without net carbon sequestration to the soil.

498   The consideration of GHG emissions should not focus solely on comparisons with fossil fuel

499   alternatives that are displaced by the use of biomass crops but should also include

500   consideration of the impacts of the cropping systems that are displaced. Dondini *et al.,*

501   (2009) compared soil carbon across a soil depth profile in an arable to *Miscanthus*

502   conversion and showed the total amount of soil organic carbon (SOC) was higher under

503   *Miscanthus* than under the arable crop and that this difference was largely due to the input

504   of new carbon. The *Miscanthus* system gained 25.4 Mg C ha^{-1} across the soil profile and this

505   increase in carbon storage within soil appeared to be largely due to the decrease in soil

506   tillage (Dondini *et al.*, 2009), an important advantage in utilising perennial crops. An

507   estimate of yearly carbon mitigation by *Miscanthus* over 15 years ranged from 5.2 to 7.2 Mg

508   C ha^{-1} yr^{-1} depending on time of harvest (Clifton-Brown *et al.*, 2007). Zatta *et al.,* (2014)

509   studied a grassland-to-*Miscanthus* conversion and showed that after an initial decline in SOC

510   due to soil disturbance resulting from cultivation at planting, SOC levels rapidly recovered
511   due to input of new carbon from *Miscanthus*. In this instance the input of more carbon from
512   *Miscanthus* did not produce a significant increase in SOC and the authors suggested the
513   additional carbon may have been utilised through increased microbial respiration, so called
514   soil priming, thus illustrating the potential for complex interactions and the need for
515   empirical data to test assumptions used in models.

516   The GHG emissions including those associated with land use change were calculated
517   comparing bioenergy feedstock and a rotational food production system it displaced (Styles
518   *et al.*, 2015). Only *Miscanthus* and rotational maize offered GHG savings when indirect land-
519   use change (iLUC) impacts were considered and the percentage of displaced production that
520   was directly replaced had a substantial impact on the estimated global warming potential.
521   However, the GHG benefits for rotational maize were offset by impacts on ecosystem
522   services, and of the six bioenergy crop systems investigated, *Miscanthus* was shown to offer
523   the greatest benefits in the provision of ecosystem services (Styles *et al.*, 2015). Tonini *et al.*,
524   (2012) used sensitivity analysis to show that uncertainties around land use change could
525   have a significant impact on LCA results. They compared four conversion pathways
526   (anaerobic digestion, gasification, small-scale CHP, and large-scale co-firing with coal) for
527   ryegrass (*Lolium perenne*), willow (*Salix spp*), and *Miscanthus* and found that only large-
528   scale co-firing of *Miscanthus* and willow offered real GHG savings compared to fossil fuel
529   alternatives. The impacts of land use change and any positive effects could be localized and
530   consideration should be given to where production might be displaced to and the impacts of
531   any further consequential land-use changes thereby incurred. The consequences of land use
532   change and indirect land use change are complex, particularly the latter, and the impacts
533   and values assigned to such change the subject of recent debate and discussion (Muñoz *et
534   al.*, 2014; Jepson and Caldas, 2017).

535   The production of biogas from biomass has received much attention recently and serves as
536   a good example of the considerations in assessing the potential impacts and possible
537   benefits of deploying *Miscanthus* as a source of biomass for biofuels. *Miscanthus* has been
538   researched as a potential substrate for the production of biogas, particularly in Germany
539   where biogas production has increased significantly in recent years (Kiesel and
540   Lewandowski, 2017; Kiesel *et al.*, 2017*a*). The cultivation of biomass to provide substrate for
541   anaerobic digestion makes up a significant proportion of the environmental impact and GHG
542   cost of biogas (Hijazi *et al.*, 2016). In the mono-digestion of maize (AD with maize alone) it
543   was the cultivation that had the largest environmental impact due to diesel fuel use in
544   agriculture and emissions linked to fertiliser use (Lijó *et al.*, 2014). *Miscanthus* has been
545   researched as a more environmentally sustainable alternative to the use of maize in biogas
546   production. LCA demonstrated biogas production using *Miscanthus*, as compared with
547   Maize, resulted in a reduction across 5 impact categories such as climate change, terrestrial
548   acidification and eutrophication of water (Kiesel *et al.*, 2017*b*). One of the benefits of
549   dedicated perennial *Miscanthus* crops is the ability to be grown on marginal lands where

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550 conventional annual crops would not provide an economically useful return. Marginal lands
551 are usually defined as such due to limitations in productivity which may occur for a number
552 of reasons; these can include abiotic stresses such as low water availability or salinity.
553 *Miscanthus* grown on marginal land was tested for biogas production and showed a cost
554 advantage over similar conversions to biogas using maize (Wagner *et al.*, 2019). Overall
555 yields of *Miscanthus* were critical in the competitiveness of gas production per hectare.
556 Potential reductions to yield of growing Miscanthus on marginal land may be offset by the
557 fact that otherwise unutilised uneconomical land is being brought back in to production.
558 Enhancing *Miscanthus'* capacity to tolerate marginal soil conditions through breeding or
559 imaginative valorisation of other potential benefits such as remediating denuded or
560 contaminated soils and incorporating this into long term rotations with food crops may
561 improve economic viability. Cultivation on overworked and nutrient denuded soils may even
562 increase overall productivity of associated food crops as soils improved by using *Miscanthus*
563 as a long term break crop are brought back into conventional food production.

564

565 **7. Traits and/or Agronomy for improved sustainability**

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

580 Miscanthus is a versatile biomass feedstock and is utilised in a number of ways across many
581 regions of the world. As discussed above, GHG savings need to be calculated against existing
582 technologies and alternative utilisations and the greatest savings and optimum conversion
583 pathways will vary from region to region. This potential complexity was illustrated by a
584 study across five European countries. At all five sites the highest energy savings were
585 achieved by combined heat and power generation via combustion (Meyer *et al.*, 2017). The
586 GHG savings were more complex: the highest savings were achieved by heat and power
587 production in Portugal (42.7 t CO_2-eq ha^{-1} yr^{-1}); however, at other European locations
588 (Sweden, Denmark, Germany, England), bioethanol production gave the highest GHG

589   savings. However, there was some uncertainty over the ability to generate the GHG savings
590   attributed to the use of fermentation residues for heat in bioethanol production which had
591   a significant contribution to the GHG savings in the scenario discussed. The study concluded
592   that the improved GHG savings were primarily associated with increased yield and that
593   composition was of comparatively lower importance but would impact other sustainability
594   characteristics such as emissions (Meyer *et al.*, 2017).

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

619   A particular challenge is perhaps one of identifying how to domesticate *Miscanthus* quickly
620   enough to maximise the potential global benefits across a short enough time scale to
621   contribute significantly to the fight against climate change. Breeding programmes are well
622   established across several biomass crops and experiments have demonstrated the potential
623   of next generation sequencing to generate markers and speed up breeding cycles using
624   genome wide association studies (Slavov *et al.*, 2014; Davey *et al.*, 2017) and optimised
625   selection indices to test strategies for efficient improvement of multiple traits (Slavov *et al.*,
626   2019).

627

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

667   unusual cold tolerance of *Miscanthus* provides an additional bonus in allowing the potential
668   benefits of water use efficiency associated with C4 crops to be utilised in temperate regions.

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

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

695

696   **9. Where to look for further information**

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

699   The context and challenges of climate change and sustainable global decarbonisation
700   including the potential contributions of carbon negative biomass crops are discussed in
701   many reviews including two recently published by IPCC (2018) and the Royal Society (2018).
702   There are a number of reviews that discuss the current status of developing bioenergy crops
703   (Clifton-Brown *et al.*, 2019) and *Miscanthus* at commercial scale (Clifton-Brown *et al.*, 2017)

704   plus reviews of the relative costs and benefits of *Miscanthus* cultivation and a general
705   consideration of land availability, land use, land conversion sustainability and competition
706   for land with food crops (Hastings *et al.*, 2009; Fazio and Monti, 2011; Valentine *et al.*, 2012;
707   Holland *et al.*, 2015; McCalmont *et al.*, 2017).

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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).
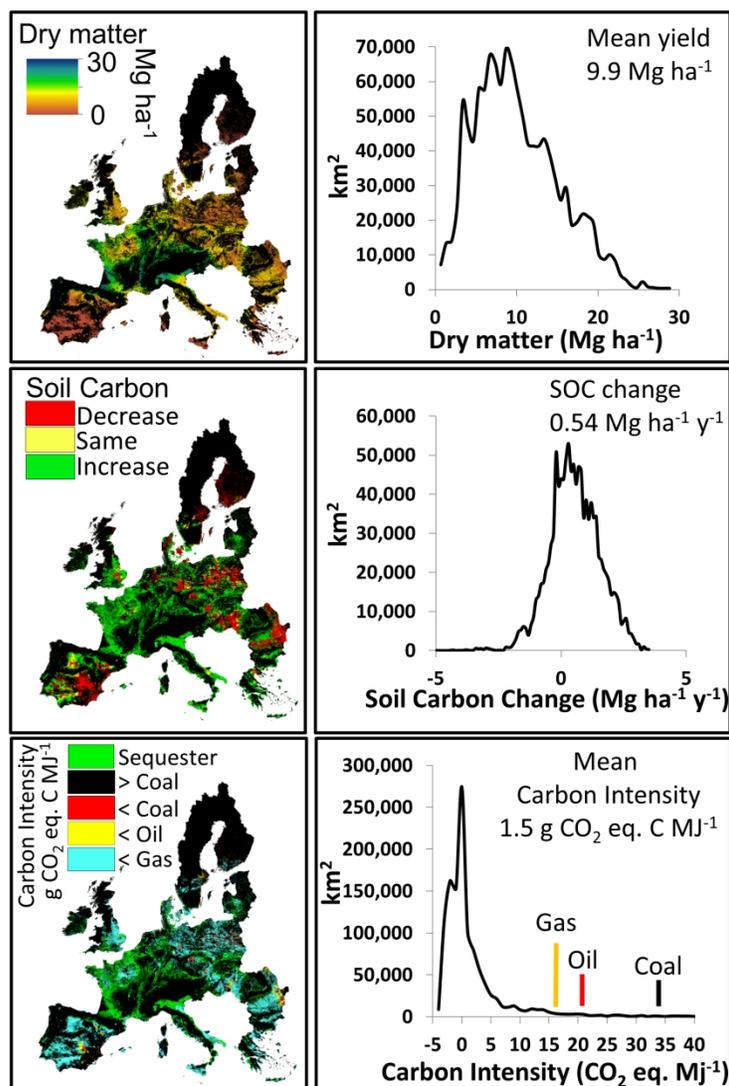
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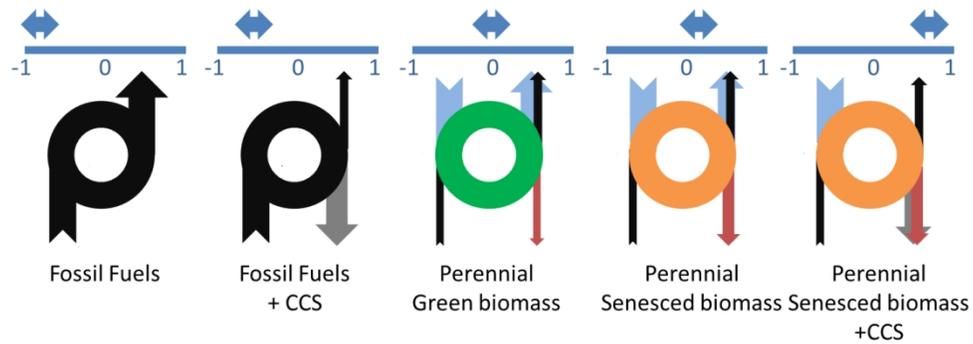
190x274mm (284 x 284 DPI)

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).

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