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RESEARCH REVIEW

Progress in upscaling *Miscanthus* biomass production for the European bio-economy with seed-based hybrids

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Abstract

Field trials in Europe with *Miscanthus* over the past 25 years have demonstrated that interspecies hybrids such as *M.* × *giganteus* ($M \times g$) combine both high yield potentials and low inputs in a wide range of soils and climates. *Miscanthus* hybrids are expected to play a major role in the provision of perennial lignocellulosic biomass across much of Europe as part of a lower carbon economy. However, even with favourable policies in some European countries, uptake has been slow. $M \times g$, as a sterile clone, can only be propagated vegetatively, which leads to high establishment costs and low multiplication rates. Consequently, a decade ago, a strategic decision to develop rapidly multiplied seeded hybrids was taken. To make progress on this goal, we have (1) harnessed

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the genetic diversity in *Miscanthus* by crossing and progeny testing thousands of parental combinations to select several candidate seed-based hybrids adapted to European environments, (2) established field scale seed production methods with annual multiplication factors >1500×, (3) developed the agronomy for establishing large stands from seed sown plug plants to reduce establishment times by a year compared to $M \times g$, (4) trialled a range of harvest techniques to improve compositional quality and logistics on a large scale, (5) performed spatial analyses of yield potential and land availability to identify regional opportunities across Europe and doubled the area within the bio-climatic envelope, (6) considered on-farm economic, practical and environmental benefits that can be attractive to growers. The technical barriers to adoption have now been overcome sufficiently such that *Miscanthus* is ready to use as a low-carbon feedstock in the European bio-economy.

Keywords: bioenergy, biomass, breeding, crop modelling, energy crops, land-use change, *Miscanthus*, perennial grasses, renewable energy

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Introduction

Biomass is a renewable source of energy, providing a storable, flexible fuel that can be readily converted to heat and/or electricity using existing well-established technologies (e.g. a solid fuel for combustion, gasification, combined heat and power, or heat alone). It can also be processed to produce liquid transport fuels through thermochemical or biochemical methods. Furthermore, during energy crop growth, the plant removes atmospheric carbon and stores a proportion in soil organic matter (Smith *et al*., 2000). Research investment to evaluate and develop dedicated biomass crops over the past 25 years has focussed on perennial species because these have higher energy yields and more favourable energy output/input ratios than annual crops (Sims *et al*., 2006). Species of *Miscanthus*, a genus comprising C_4 rhizomatous grasses from Eastern Asia, combine high photosynthetic efficiency with tolerance to temperate climates and have many of the characteristics that are desirable in a perennial biomass crop. The clonally propagated interspecies hybrid *Miscanthus × giganteus* ($M \times g$) has been used in this way since 1983 (Lewandowski *et al*., 2000; Dohleman & Long, 2009; Heaton *et al*., 2010; Clifton-Brown *et al*., 2015). Field trials and extrapolations using yield models (Hastings *et al*., 2009a, 2014) have demonstrated that *Miscanthus* is a suitable biomass feedstock for a wide range of climates and soils. These trials have also generated information on the impact of the crop on the environment (Milner *et al*., 2016); analyses of a range of issues, including greenhouse gas mitigation, soil carbon and biodiversity, show that the environmental benefits outweigh costs in most situations (McCalmont *et al*., 2015).

With careful attention to agronomy during establishment, *Miscanthus* (mainly $M \times g$) has proven to be productive on lower grade agricultural land, including heavy metal contaminated (Nsanganwimana *et al*., 2014; Pidlisnyuk *et al*., 2014) and saline soils (Sun *et al*., 2014; Stavridou *et al*., 2016). *Miscanthus* can therefore contribute to the sustainable intensification of agriculture, allowing farmers to diversify and provide biomass for an expanding market without compromising food security.

Spatial constraint maps have indicated that 8.5 Mha of lower grade land in the UK is suited to biomass crops (Lovett *et al*., 2014). Meanwhile, Terravesta Ltd., a UK developer of *Miscanthus*, argues that 10% of the land area of most arable farms is economically marginal for reasons including

1. Insufficient soil depth to ensure a reliable yield in dry years,
2. The presence of stones which damage machinery,
3. Awkward field shapes which are not accessible using modern arable machinery that is based on operating widths of 12 and 24 m (compared to that used for *Miscanthus* of 4–8 m), and
4. Infestations with recalcitrant weeds such as black-grass (*Alopercurus myosuroides*).

Any of these, singularly, or in combination, can make annual food production crops uneconomic, and these land areas might therefore be more profitably used for perennial biomass crops. There is anecdotal evidence from farms in the UK that planting *Miscanthus* on 10% of the more marginal land leads to an increase in productivity on the rest of the farm. Time and resources spent on marginal land can be out of proportion to its economic value and impact negatively on other parts of the business; this phenomenon of optimising use of better quality land is discussed in 'Reaping the Benefits' (The Royal Society, 2009). In 2014, discussions at the UK Land-Energy Nexus Workshop in Cambridge (see www.wholesem.ac.uk/) concluded that 0.9 Mha was a realistic target for perennial biomass crops in the United Kingdom by 2050. GIS and modelling analysis suggest cultivating *Miscanthus* on up to half of this 0.9 Mha would be reasonable (Hastings *et al*., 2014; Wang *et al*., 2014), with the remainder being more suited to other biomass crops. This is strikingly close to the 0.35 Mha of arable land for biomass production estimated in the UK Biomass Strategy 2007 (DEFRA, 2007), and is reasonable when compared to arable crops that contribute to UK's biofuel consumption (DEFRA, 2015).

Two UK policies have driven a biomass market of greater than 10 million tonnes in 2015. Firstly, renewable obligation certificates (ROCs) have resulted in electricity generation via conversion of coal-fired power stations to biomass firing or co-firing, using in excess of 5 million tonnes of biomass per year, while a range of smaller dedicated biomass power stations are operating or under development, using forest residues, agricultural straw and energy crops as fuel. Secondly, the renewable heat incentive (RHI) is stimulating small- and medium-sized biomass boiler installations, mostly below 1 MW in capacity, and likely to consume 1.5–2 million tonnes of biomass in 2015. Currently, it is estimated that over 75% of biomass used in the United Kingdom for large-scale electricity is imported (J. Scurlock, unpublished data; CarbonBrief.org). An analysis of the UK Renewable Obligation data for 2013–14 (OFGEM, 2015) for biomass consignments by country of origin shows that only 34 of 280 biomass consignments were sourced from within the UK. Domestic biomass production shortens supply chains, thereby reducing greenhouse gas emissions, assists with balance of trade payments for energy, improves soil fertility, and can help grow the rural economy. In addition to its use in direct combustion, there is considerable scope for other end uses of *Miscanthus*, for example anaerobic digestion (Klimiuk *et al*., 2010; Kiesel & Lewandowski, 2015), gasification and pyrolysis (Hodgson *et al*., 2011) or enzymatic hydrolysis to produce materials (Velasquez *et al*., 2003; Uihlein *et al*., 2008; Ragoubi *et al*., 2012), fuels (Brosse *et al*., 2012), chemicals and plastics.

So why has the uptake of *Miscanthus* been so low to date? In 2009, the planted area of *Miscanthus* in the United Kingdom was estimated as 13.5 Kha (Don *et al*., 2012) and the 2015 estimate is about 8 kha, as less successful plantation areas have been reverted to conventional agricultural crops. In Table 1, we list a range of barriers along the development chain and we provide a matrix of solutions with a focus on the introduction of seed-based hybrids. In brief, seeded cultivars have

1. high multiplication factors (mfs; propagules per m^2 of mother field is >1500, compared to 10–50 for rhizomes of $M \times g$) and are cheaper than *in vitro* cloning,
2. simple transport and storage logistics unlike cloned rhizomes which require up to 2 Mg fresh weight ha^{-1} or plantlets from *in vitro* cultures,
3. faster introduction of new cultivars with
   a more potential resilience to abiotic stresses such as drought and biotic stresses from pathogens and
   b improved biomass composition (reduced moisture, ash and potassium levels). Plant breeding plays a key role in creating high-yielding, resilient, homogenous, seed-propagated cultivars for developing biomass supply systems and underpins the transition from today's niche crop into tomorrow's large-scale, commercially profitable biomass production.

Miscanthus breeding at Aberystwyth University's, Institute of Biological, Environmental and Rural Sciences (IBERS), began in 2004. Initially, the objectives were to breed a diverse range of *Miscanthus* hybrids suited to a range of growing conditions for use as a biomass fuel. In this context, following extensive multilocation field trials, several individual genotypes were selected from a pool of landraces and from the progeny of crosses. While these genotypes have advantages relative to $M \times g$ such as lower moisture content at harvest, it remained commercially impractical to upscale them to millions of hectares by clonal propagation. In 2007, together with CERES Inc., a US crop biotechnology company, we began the development of seed-based hybrids. In this article, we outline the steps taken to date to upscale the *Miscanthus* crop. These are being developed further via a continuing international breeding and agronomy research programme with public and private investors. We have removed most of the barriers that previously prevented upscaling. The range of attributes across the high-yielding hybrids of *Miscanthus* makes it suitable for many uses and environments, and it is therefore a biomass crop that can be upscaled across Europe. However, we recognise that diversity of biomass type is appropriate, and while we envisage *Miscanthus* as a key component of a European biomass industry, we are not proposing it as the sole source of European biomass.

Novel germplasm and breeding

Germplasm collections in Asia, led by IBERS (Aberystwyth, UK), with colleagues from Julius Kühn-Institut (JKI) (Braunschweig, Germany), working with partners in China, Japan, South Korea and Taiwan, were made to increase the genetic diversity available for breeding. The key species collected in Asia included *Miscanthus sinensis*, *M. sacchariflorus* and *M. floridulus* which all grow over wide climatic ranges (Clifton-Brown *et al*., 2011b). The collections abided by the principles of the UN Convention on Biological Diversity (CBD), which recognises national sovereignty over indigenous germplasm. A supplementary agreement to the CBD, the Nagoya Protocol ratified in 2010, sets out the road map for fair and equitable sharing of the benefits arising from the use of genetic

Table 1 Major barriers and research-based solutions for economically effective large-scale biomass production. These are arranged from top to bottom along the production to utilisation chain

Barriers		Research towards solutions		
Barrier type	Specific examples	Breeding	Agronomy	Policy
Growing the crop				
High establishment costs	Clones are both expensive and difficult to upscale	Develop seed production methods	Learn how to use seed efficiently with optimised sowing densities	Reduce costs sufficiently to remove the need for planting grants
Immature field planting technology	Slow and unreliable establishment	Select hybrids with faster first growing season establishment rates	De-risk planting with modular plantlet systems (plugs) in the short term, whilst innovations for reliable direct sowing systems are developed	Map feedstock production opportunities with different planting systems
Resistance to land use change by the growers and the public	Perception of invasive risk, particularly in seeded hybrids	Select non flowering hybrids with low rhizome creep rates in the production zone	Protocols for both planting and reversion after crop life are robust with overall positive impacts on soil organic carbon levels	Promoting landuse change to better manage farm carbon footprints
Uncertainty in the yield expectations due variations in abiotic stress	While $M \times g$ has demonstrated cold and salinity tolerance in trials, it is susceptible to prolonged drought	Screen diverse parental germplasm and hybrids for resilience traits	Select hybrids with improved salt, cold and water tolerance from multi-location trials	Map the additional crop production areas taken in by marginal land
Biotic stress (pathogens, diseases and weed competition)*	Limited problems to date, but in time as areas expand these are more likely	Ensure a diversity of hybrids are used in the future	Create low input practical control protocols	Prevention through development of best practice guidelines
Harvesting				
Low quality biomass resulting from high moisture, ash, alkalis and silica contents*	Corrosion from high K and Cl when biomass in combusted	Select hybrids with appropriate senescence properties	Matching harvest regimes to crop, climate, enduse specifics	Setting realistic ISO standards for pellets and chips
A bulky product (low density) for efficient storage, stability and transport*	$M \times g$ is challenging to pellet	Characterise morphotypes and processability	Seek optimum processing plant scale and crop haulage balance for optimum whole supply chain emissions	Perform LCA on sustainabilty to give accreditation to the feedstock chain

Table 1 (continued)

Barriers		Research towards solutions		
Barrier type	Specific examples	Breeding	Agronomy	Policy
Connecting with markets				
Supply chain confidence	High risks due to unstable prices and uncertain markets	Demonstrate economic advantages of new hybrids on a range of biomass value chains	Reduce technical risks	Guarantee minimum pricing of feedstock for growers by stabilising base prices for the lifespan of the crop
Competition from other crops and land uses	Use of more profitable or flexible annual crops	Produce hybrids for lower grade lands	Maximise yields on lower grade lands to achieve profitability	Consistent policy on feed in tariff schemes
Lack of sustainability accreditation*	Inadequate history for the *Miscanthus* crop	Maximise and measure production efficiency of potential commercial hybrids	Quantify production efficiency to provide inputs for LCA	Show that LCA outputs fit with government sustainability targets
Supply chain co-ordination	Different parts are not joined up	Understand desirable and undesirable traits for different products/processes in order to influence breeding choices	Ensure sustainability and unrivalled emissions and sequestration data through best practice	Create economic incentives for supply chain co-ordinators

*Not covered extensively in this paper.

resources. Implementation of the Nagoya protocol has been championed in Europe by the UK Department for Environment, Food and Rural Affairs (DEFRA) and Kew Royal Botanic Gardens in London. As *Miscanthus* germplasm collections led by the breeders in Aberystwyth are for use in potentially commercial applications, it has been necessary to develop and sign agreements that meet the CBD criteria and follow the Nagoya protocol.

Wild accessions from Asia were admitted to United Kingdom under a licence from DEFRA and quarantined at IBERS. Once germplasm was released from the quarantine nursery, trials were planted at three locations in Europe and the US in different climatic zones to assess phenotypic traits and climatic adaptability. Selections of the top accessions for key desirable traits were made in the second and third growing seasons and entered into a crossing programme at Aberystwyth and Texas.

The environmental conditions required to initiate flowering varies widely within and between species. Data from Asia and from European trials, combined with observations from glasshouse experiments at IBERS, were used to derive process descriptions for mathematical models to predict the environmental conditions needed to synchronise flowering (Jensen *et al.*, 2011, 2013). Thousands of exploratory two parent crosses were attempted within and between species in diverse accessions. As *Miscanthus* is highly self-incompatible, almost all seed set are hybrid seeds. Two parent, rather than multiparent, crosses were preferred to reduce the genetic variation in the 'F1 seedlings' which would constitute the production crop. Seedlings from exploratory crosses were raised in the glasshouse before field planting in nurseries in multiple locations across Europe and the United States to span a diversity of climates and to identify key parental combinations. From cycles of hybridisation and selection in challenging as well as good growing locations, a small number of hybrids have been selected that are performing well in trials relative to $M \times g$. Parents of these promising hybrids have been cloned to produce more plants which are being used for seed production to enable larger plot trials of their progeny in more locations. These field scale trials have been made possible by precommercial scale seed production in the United States. As in all breeding programmes, the ongoing production of new parents and hybrids, together with testing in putative production environments, can, over the years, provide the diversity of products required for successful, extensive agriculture – something not possible with use of $M \times g$ alone.

Seed production technology

Xue *et al.* (2015) identified five main approaches for *Miscanthus* establishment including (1) direct planting of rhizomes produced in a 'mother field' (with an estimated annual mf of ×10, costing €1900–3400 ha^{-1}), (2) plantlets from clones, produced using indirect rhizome propagation in plugs (mf ×30, ~€4300 ha^{-1}), (3) nodes produced in modules (mf ×30, ~€4000 ha^{-1}), (4) through seed (no mf or cost given) and (5) through micropropagation (mf ×960, >€6000 ha^{-1}). Xue *et al.* could give no estimates for seed propagation because no systems had been developed. Our programme has focussed on developing the systems for seed propagation for reasons already stated.

We are continuously refining our strategies to synchronise flowering time between diverse parents to allow cross pollination. Figure 1a shows an example experimental crossing plot (known as a 'block') in the United States, where flowering synchronisation was achieved for interspecific crossing of *M. sinensis* × *M. sacchariflorus*. Panicles with ripe seed need to be collected 3–4 weeks after pollination, but before the florets start to detach from the racemes. Threshing methods vary between the species type which have different seed sizes. Post-threshing seed quality tests are essential to protocol improvements. The net multiplication factor for the cross in Fig. 1a was >1500× for the final viable seed.

Developing agronomy

As *Miscanthus* seeds are small (0.5–0.9 mg, Fig. 1b), shallow sowing is required; as in many species, light regulates dormancy termination. Evidence on the light requirements for germination in *Miscanthus* is conflicting, possibly because only a few photons of light are needed. At the surface, it is difficult to achieve reliable seed-to-soil hydraulic contact giving little control on the timing of germination if soils are dry following sowing (Anderson *et al.*, 2015). Further, base temperatures for *Miscanthus* germination range from 9 to 11.5 °C (Hsu *et al.*, 1985; Nishiwaki & Sugawara, 1997; Clifton-Brown *et al.*, 2011a). This is 6 °C higher than *Lolium perenne* ('Aber DART') another grass that is always established by direct seed sowing in the United Kingdom. A spatial modelling analysis showed that for much of the EU, low spring temperatures would limit the potential for direct sowing because seed would germinate only from late May onwards (Clifton-Brown *et al.*, 2011a). However, from late May onwards, soil surface dryness and competition from C_3 weeds contribute to germination failure and growth suppression. Furthermore, when seedlings do establish late, they may not grow well enough before autumn to produce sufficient rhizome for successful overwintering. All these factors combine to make direct sowing using current agronomy challenging.

The chances of seedling establishment in the temperate zones can be improved by covering the seed bed after sowing with photodegradable transparent polymer mulch films, as is used for maize (Keane *et al.*, 2003). These film coverings create conditions conducive to

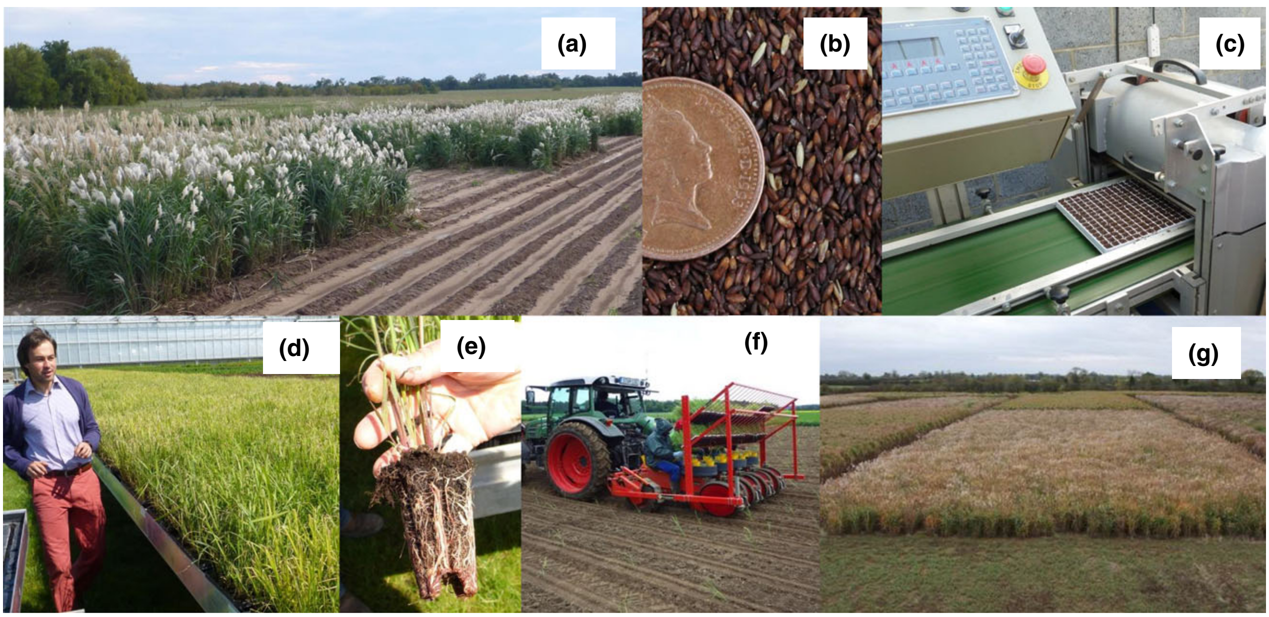

Fig. 1 Steps taken to develop seed-based *Miscanthus* hybrids: (a) Field seed production trials in CERES, USA. (b) Threshed *Miscanthus sinensis* seed with a British pound coin for scale. (c) High throughput plug sowing. (d) Dr. Michal Mos, checking plugs which are hardening for field planting in Lincoln. (e) A field-ready plug. (f) Mechanical planting of plugs with a Unitrium plug planter in Stuttgart, Germany. (g) Large-scale replicated 0.25 ha plot trials in Lincoln, UK.

seed establishment by both raising the average soil surface temperature by about 4 °C and by maintaining soil surface moisture. In small field trials to date, direct sowing experiments have used high sowing rates (50–300 seed m^{-2}). At best, emergence has been about 10% of the seed sown. Experience has shown that seedling establishment is highly sensitive to soil tilth and soil moisture at the time of sowing, even when films are used. A negative effect of films is to stimulate volunteer weed seeds. Furthermore, it is difficult to control plant density with direct sowing, and where subsequent plant densities are too high (>2 plants m^{-2}), it is likely that long-term stand yield performance will be reduced. In contrast, where plant densities are too low, at best the crop will take longer to reach productive yields, and at worst, be swamped by competition from weeds.

For the reasons described above, recent work has focussed on sowing seed in modular plugs in glasshouses. However, without sufficient attention to detail, it is still possible to have 20–40% of plugs without seedlings, known as 'blind plugs'. The causes for these losses include seed immaturity at harvest, damage to the seed coat during threshing, seed storage conditions and duration and seed sowing accuracy onto the compost surface. Therefore, before seed sowing in plugs is performed, a germination test is required to estimate the viability. Protocol optimisation, exploring factors such as different composts, temperatures, radiation and fertiliser regimes, has resulted in practices that produce strong plants ready for field transplanting in early May.

In 2014, in precommercial scale trials, an average of 94% field establishment using plug and film was achieved at six locations distributed in the UK with four new seeded hybrids. This was similar to establishment rates with rhizomes when film was used, and 5% better than when no film is used (Ashman, pers. comm.).

Another consideration relating to establishment is the time to full yield; $M \times g$ typically requires 4 years to reach full productive potentials in cooler locations (Clifton-Brown *et al.*, 2001, 2007), and this represents an economic barrier to farmer uptake of the crop. Our current target is 70% of mature yield by the end of the second growing season. In Aberystwyth, films laid over plugs planted in May 2011 doubled the total biomass per plant in the first growing season compared to plugs without film (M.H. Jones unpublished data). Agronomic trials are underway to help achieve this target by extending the growing season length with earlier planting of plugs in March–April. Films offer protection during this period when there is still a high risk of spring frosts. However, the higher glasshouse energy inputs required to produce plugs for earlier planting dates will need to be evaluated against the gains in productivity.

To improve establishment, additional research on weed control strategies, including herbicide regimes, is needed. Determining the efficacy of postemergence herbicides is complicated by the multiple interactions between climate, soil and mulch film. Such tests are currently being performed in Seoul National University, South Korea.

At present, the establishment costs of plug and film agronomy are comparable to $M \times g$ rhizomes at about £1500 (€2100) ha^{-1}. However, as plug-based techniques can be scaled up to millions of plants per year, these economies of scale mean costs are projected to halve. Systems for planting plugs into the field are also highly scalable using machines developed for the vegetable industry (Fig. 1c, f) but will need further development to make them suitable for planting on more marginal lands, especially those with high stone content. Attention to, and the development of, detailed agronomic protocols for different climatic and edaphic conditions that are scalable are key to the successful upscaling of the *Miscanthus* cropped area.

Harvest technology

Harvesting techniques, climatic conditions and plant morphology all interact to affect biomass quantity and quality and the resultant options for downstream biomass utilisation. In the United Kingdom, France and Germany, following cold winters which force $M \times g$ to ripen to below a moisture content of 25%, self-propelled forage harvesters (normally used for maize) have been used successfully to produce chips from $M \times g$ crops. This direct chipping approach results in biomass losses of only 5% (Meehan *et al.*, 2013b). The chips dry well in covered storage; however, *Miscanthus* chips have a number of draw backs. Firstly, they have a low bulk density (150 kg m^{-3}); this leads to high storage costs and limits markets to the proximity of available crop. Secondly, the low bulk density reduces the fuel mass in the combustion chamber, which lowers the thermal output of most boilers. Thirdly, unless the chip has been produced using a high precision chop forage harvester, bridging and clogging can be a problem with automated feed systems.

Meehan *et al.* (2013a) calculated that the overall net energy delivered to the end-user in terms of harvestable material by the direct cut and chip system was 12.45 GJ (Mg DM)$^{-1}$ compared with 11.78 GJ (Mg DM)$^{-1}$ by the mow and bale system, making direct cut the more efficient system even up to a transport distance of 400 km. This approach discounted the energy costs of harvesting and transport from the gross energy content of ~17 GJ (Mg DM)$^{-1}$. In France, Novabiom (www.novabiom.com/en) are harvesting with the direct cut and chip method. In United Kingdom and Ireland, where winters are often too mild to force full senescence and ripening in $M \times g$, mowing the crop into a swath (or windrow) in February and March to allow the base of the cut canes to die and dry for about 4–6 weeks before baling is preferred, because this method reduces the moisture content in the standing crop from ~30% to 45% down to 12–16%. Reduced moisture content both increases the net calorific value of the biomass as harvested and prevents the microbial breakdown of biomass in the stored bales. Recent developments in large square high density (Hesston style 120 × 120 × 250 cm) balers have significantly increased bale weights from 400 kg to 650 kg for $M \times g$ which will reduce transport and storage costs. Bales can be used whole, broken up or processed into other products. In the United Kingdom today, most of the $M \times g$ crop is pelleted for use in power stations and boilers.

A 'large-scale' scientific trial (5 ha), planted in Blankney Estates, Lincoln, UK, in 2012, with four diverse shorter stature seed-based hybrids and $M \times g$ as a control, was used for harvest tests in spring 2015. This showed that shorter growing hybrids with thinner stems had benefits of lower moisture content, significantly higher bale weights and required less power to pellet (Michal Mos, pers. comm.). But, compared to $M \times g$, short stature types were lower yielding and the pellets were 20% less dense. These measurements of genotype–hybrid-specific biomass drying, quality and ease of processing will be fed back into breeding selections.

Harvesting systems equipped with low ground pressure tyres have the significant advantage of reducing the compaction from wheels which can damage the crop (O'Flynn *et al.*, 2014). The machinery wheel spacing also needs to be considered when designing field row spacing to minimise crop damage.

Advances in harvesting techniques such as those outlined here will help to close the yield gap between experimental trials and commercial plantations (Zimmermann *et al.*, 2014).

Yield potential and assessment of the regional production potential

Trials of novel hybrids (mainly, but not exclusively interspecies) in Europe (UK, Italy, Germany, Turkey, Russia, Ukraine and Poland), have extended the range of geographic, edaphic and climatic conditions under which *Miscanthus* has been grown in field plot trials. These trials are being used to improve descriptions needed for hybrid-specific modelling using detailed phenotyping protocols for a range of growth traits. The observations of crop and plant growth include the dates of plant emergence, flowering and senescence, harvest yields, timing of leaf expansion, height, photosynthesis rates, water use and growth, as well as multiyear observations of stand establishment, overwinter survival and reactions to drought. The plant phenotypic data are being combined with a spatial characterisation of the soil profiles and water-holding capacity of the experimental sites and a complete time series of meteorological observations of temperature, rainfall, wind run, relative humidity and soil moisture and temperatures at several depths (A.F. Hastings unpublished data).

In addition to better understanding of novel hybrids, these multilocation trials have also included $M \times g$ and have enabled improvements in the MiscanFor model (Hastings *et al.*, 2009b) to be made so that it more accurately predicts crop behaviour under the edaphic and climatic conditions observed in these field trials for this current commercial standard. It has also enabled the different crop behaviours of the hybrids to be added to the model parameterisation. As a result of this work on model-based estimation of $M \times g$ and hybrid crop yield and survival, the bioclimatic envelope where both $M \times g$ and the hybrids can be grown as a viable biomass crop has been extended into central Eurasia. Previous modelling underestimated both the yield and bioclimatic range of $M \times g$ (Fig. 2a) and, in addition, experiments and modelling show that $M \times g$ does not give the best yield in all Eurasian conditions. This improvement shows that field yields of *Miscanthus* crops are in reality closer to that of the theoretical 'hi-tech' hybrid proposed by Hastings *et al.* (2009a). This extends the predicted geographic range for cultivation of a range of *Miscanthus* genotypes further north and east, as recent trials in Russia and Ukraine demonstrated that plants can survive cold winters if there is an insulating snow cover and produce harvest yields greater than 10 Mg ha^{-1} (Fig 2b).

On farm benefits

There are significant environmental benefits in a move from annual, intensive cropping to perennial, low input extensive *Miscanthus* production (McCalmont *et al.*, 2015), particularly where this conversion takes place on less productive, more resource-intensive areas of land. Allowing this land the time to recover from annual cultivations improves soil structure/stabilisation, reduces erosion and increases organic matter and faunal and floral abundance and diversity (Kahle *et al.* 2001; Hansen *et al.* 2004; Felten & Emmerling 2012). Using *Miscanthus* as a 10- to 15-year break crop could ultimately produce higher quality farm land over the long term, particularly if considered as a long-term rotation on overworked arable soils. Environmental gains of planting *Miscanthus* on long-term grasslands are not as clear cut as on arable land, but reductions in fertiliser use will reduce farm greenhouse gas emissions, improve GHG

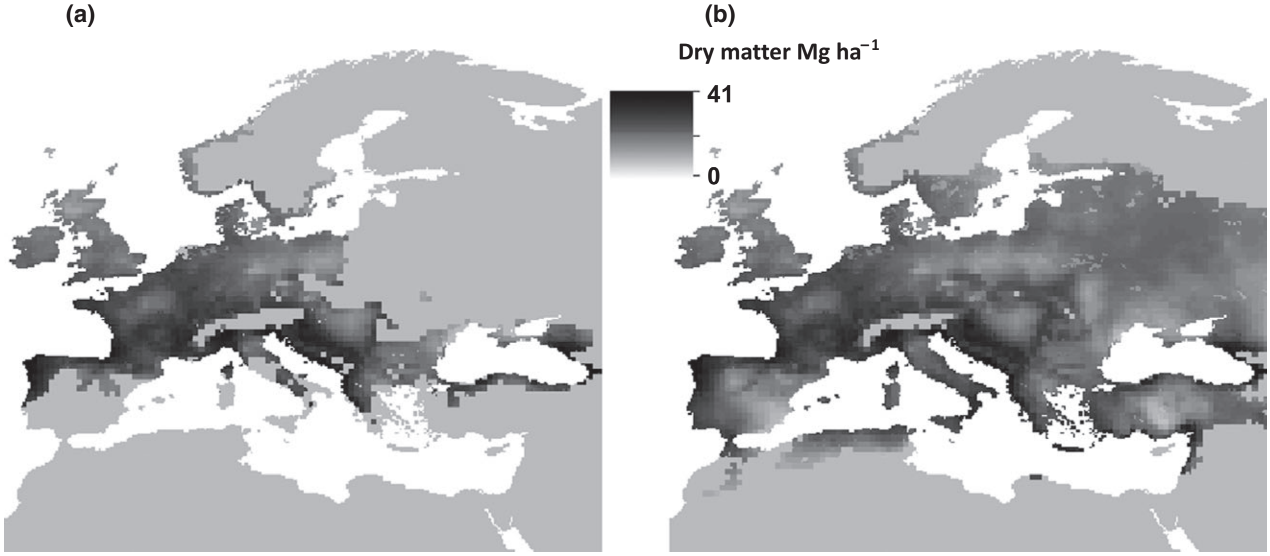

Fig. 2 A revised* crop yield prediction for $M \times g$. Yield is displayed in grey scale from 41 (black) to 0 Mg ha^{-1} (Grey). The original $M \times g$ bioclimatic envelope (Hastings *et al.*, 2009a,b) is shown in (a) and the new estimation of the bioclimatic envelope for $M \times g$ and the new trialled hybrids is shown in (b) which is based on recent climate data 2000–2009 and FAO/IGBP plant available water estimates on a 5 min grid. The new cold limit considers the data from infield soil temperature measurements and the overwinter survival success. The new drought limit is based on observed infield drought responses and water balances with estimates of plant available water derived from depth and soil textures. This high-level analysis does not identify the marginal lands within the grids where the yields may be lower than those indicated. *Revised 2015, for the earlier version see Hastings *et al.* (2009a,b).

balances and nitrate leaching, while impacts on soil carbon stocks and soil biota will be minimal in these perennial to perennial system changes.

Growing *Miscanthus* has low labour and machinery inputs after establishment due to its perennial nature. It fits well into arable, farming regimes. Early spring harvesting avoids clashes with most other field operations, while the combination of low annual costs and consistent yield patterns reduce the volatility risk in both output and margin that is an increasing factor of growing almost every other agricultural commodity. Additionally, water quality legislation and regulations (such as nitrate vulnerable zones and Local Environmental Risk Assessment for Pesticides) offer an opportunity to grow *Miscanthus* as a viable crop on parts of farms that would otherwise remain unproductive.

Growers report significant whole-farm benefits from growing the crop. These include improved profitability of marginal areas of the farm, as well as reducing the time and resources spent on these areas; improved yields on the remaining arable areas compensate fully for the food production loss from the land on which *Miscanthus* is grown. The perennial nature of *Miscanthus* allows growers to significantly restructure overhead costs (in particular energy and labour) and reduce working capital and finance requirements. Together, these strengthen farm businesses and help to secure and underpin the rural economy.

Farmers who supply the retail sector directly face additional pressures to demonstrate year-on-year reductions in carbon footprint, and this is likely to be an industry-wide requirement in the future. Low-input *Miscanthus* can make a significant contribution to these reductions by being in the mix of cultivated crops. This can be further enhanced, for example, through home or farm use of the harvested crop for heat and/or power for grain drying, processing, poultry, housing and office space, etc.

Delivering the crop

Despite the benefits discussed above, potential growers have been slow to adopt *Miscanthus* for the reasons listed in Table 1. In the UK, commercial development was pioneered from around 1998, principally by a company called Bical Ltd. This resulted in the UK having the largest planted area in Europe (13 kha) by 2010. The company promoted long-term grower contracts for *Miscanthus*, but the lack of a secure market for the biomass and establishment problems with early attempts at commercial scale rhizome propagation, resulted in a reduction in farmer confidence and total planted area. The situation was further exacerbated by UK policy instability and now the estimated production area is 8 kha. However, despite these setbacks, successor companies have developed stable commercial arrangements to supply *Miscanthus* for energy generation. Efforts to diversify the markets for *Miscanthus* biomass have been ongoing throughout Europe, including via an umbrella organisation; Internationer Verein für *Miscanthus* und mehrjährige Energiegräser (MEG) e.V. Participants in MEG include academics, commercial growers and end-users. NovaBiom (France), while developing *Miscanthus* biomass primarily for fuel, are also supporting research into using *Miscanthus* for a range of uses such as poultry bedding and in construction/insulation materials.

As discussed, growth in the planted area of the crop was previously suppressed by market immaturity, lack of confidence in a long-term business model and the slow speed of return on investment. However, since 2012, companies such as Terravesta in United Kingdom and NovaBiom in France have performed much to overcome these barriers, principally by establishing a reliable market through buying *Miscanthus* biomass off-farm on long-term contracts and selling *Miscanthus* energy products to a range of end-users. A number of other initiatives have contributed to a recent growth in planted areas. Terravesta has initiated 'upward only' price index annual reviews to protect businesses over 10-year period, which is more than long enough to yield a strong return on initial investment for the grower under most circumstances, while simultaneously guaranteeing security of price and supply for the end-user. Building on the experience gained over the past 15 years, agronomic practice guidance has been provided to growers to ensure they get the most from the crop in yield, quality and financial return. Reliable planting regimes and rhizome sources that deliver high establishment rates and high plant vigour have halved the $M \times g$ cost of establishment to the grower. Preplanting, planting and contract-linked professional support and agronomy are provided, especially targeted to sites that are shown to be underperforming when compared with benchmarks. An active multisite trials programme to introduce seed-based *Miscanthus* is being developed. Finally, commercial developers are participating in technical forums and hosting farm visits to disseminate information and best practice to existing and potential growers and contractors in the supply chain.

Expanding the market for biomass

The expansion of the *Miscanthus* crop depends on the ability of the technology to deliver within environmental and economic constraints. Biomass as a fuel has to compete with other forms of energy, and the market value of *Miscanthus* is dependent on the values of competing fuels such as coal, gas, oil and imported wood pellets, and the production costs of nuclear and other renewable energy such as solar, wind, wave, tidal and hydro. Subsidies also have a significant impact on the energy market. Oil price is generally the determining factor for the costs of other fossil fuels, but the development of technologies such as multiple horizontal wells and multiple zone fracturing has dramatically changed the dynamics of the market by allowing the economic production of unconventional oil and gas (Ajaya *et al.*, 2013). Oversupply in these commodities has reduced their market value, which in turn has caused the price of coal to slump and reduced the economic value of other fuels including biomass. However, subsidies for biomass exist in many countries (e.g. the UK's ROC and RHI, mentioned earlier), and the COP21 Paris agreement of December 2015 is expected to drive public intervention in the energy sector to reduce greenhouse gas emissions. Indeed, the fifth assessment report of the IPCC (IPCC, 2014) indicated that all key mitigation options (increased energy efficiency across the board, all renewable, carbon capture and storage) need to deliver in the coming 4 decades on a vast scale and that 250–300 EJ (a quarter to a third of the world's energy supply in the second-half of this century) may need to come from biomass to make that possible. With those targets, the need for net negative carbon emissions (via measures such as carbon capture and storage, and the growth of biomass) is necessary on a large scale.

Miscanthus × *giganteus* will continue to play a role in biomass production where farmers have developed their own system of rhizome establishment on agricultural land of reasonable quality. However, expansion into marginal agricultural land will require the development of stress tolerant novel hybrids that can be propagated on a large scale via seeds and can be established and managed safely at a low cost. Farmers will also need to be involved in the development and upscaling process, for example by demonstrating a functional value chain and by bringing biomass to well-developed markets.

Concerns over competition between crops for food and fuel are often raised, but there is a strong case for farming to produce both (Valentine *et al.*, 2012), and it has been argued that food production and fuel supply are highly correlated (Webber, 2015). As argued here, a conservative estimate of available lower grade land for *Miscanthus* is 0.45 Mha, which would produce 20–25 TWh of heat annually, enough to cover the entire off gas grid heat requirement of the UK (Wang *et al.*, 2014). Using current biomass prices for large-scale electricity production (which assumes compositional suitability for these systems – an area of intense research and development activity), the annual value of ~5 million tonnes of crop would be ~£300 million p.a. However, without the breeding of seed-based hybrids and the agronomic developments described here which overcome many of the barriers in Table 1, planting on this scale in the UK would not be practical in a time frame relevant to a substantial contribution to the greenhouse gas reduction targets of the UK government.

Europe needs to move away from discussing the need for low-carbon crops to the realisation that they now exist and are financially, environmentally and agronomically viable. The research and development undertaken to domesticate *Miscanthus* means it is now one such crop. A consistent policy environment is now required to deliver these benefits to the wider economy.

Conclusions

- Supply chain economics are the major determinant for successful crop uptake. This research programme has been focusing on technologies that reduce costs and enable large-scale production.
- Interspecies hybrids have been produced from Asian germplasm that are likely to match and exceed commercial $M \times g$ yields on both higher and lower grade lands. These hybrids are propagated from seed.
- A seed-propagated crop is scalable to reach the levels needed to make significant impacts on renewable energy targets at national and international scales and achieve greenhouse gas mitigation targets. Hybrid seed production methods have been established with large multiplication factors.
- The breeding systems established enable a pipeline of diverse, improved and industry-suited hybrids to be delivered over time to fulfil industry needs more effectively.
- Agronomic protocols have been developed for Europe to grow the crop from seed reliably using plantlets in modules capable of being used in high throughput planting systems.
- Harvesting approaches vary according to a complex interaction between hybrid phenotypic features and climate. Densification into pellets is key to overall economic functioning of the large-scale supply chain.
- GIS spatial modelling based on extensive yield data for $M \times g$ and recent climate data is now ready to extend to new hybrids as field trial data matures for the novel seed-based hybrids. *Miscanthus* breeding and agronomy must now focus on exploiting land areas which are less suitable for food crop production.
- Research has moved forward the opportunity for more effective market uptake. Policies are crucial to provide the market stability needed to ensure profitability at all stages along the biomass chain.
- *Miscanthus* is being developed further as part of the overall energy mix via a continuing international breeding and agronomy research programme with public and private investors. We have removed most of the barriers that previously prevented upscaling. The range of attributes across the high-yielding hybrids of *Miscanthus* makes it suitable for many uses and environments, and it is therefore a biomass crop that can be upscaled across Europe.

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References

Ajaya B, Aso II, Terry IJ *et al.* (2013) Stimulation design for unconventional resources. *Oilfield Review*, **25–2**, 34–46.

Anderson EK, Lee D, Allen DJ, Voigt TB (2015) Agronomic factors in the establishment of tetraploid seeded *Miscanthus x giganteus*. *GCB Bioenergy*, **7**, 1075–1083.

Brosse N, Dufour A, Meng XZ, Sun QN, Ragauskas A (2012) *Miscanthus*: a fast-growing crop for biofuels and chemicals production. *Biofuels Bioproducts & Biorefining-Biofpr*, **6**, 580–598.

Clifton-Brown JC, Long SP, Jørgensen U (2001) *Miscanthus* productivity. In: *Miscanthus - for Energy and Fibre* (eds Jones MB, Walsh M), pp. 49–67. James and James (Science Publishers), London.

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

Clifton-Brown J, Robson P, Sanderson R, Hastings A, Valentine J, Donnison I (2011a) Thermal requirements for seed germination in *Miscanthus* compared with Switchgrass (*Panicum virgatum*), Reed canary grass (*Phalaris arundinaceae*), Maize (*Zea mays*) and perennial ryegrass (*Lolium perenne*). *GCB Bioenergy*, **3**, 375–386.

Clifton-Brown JC, Renvoize SA, Chiang Y-C *et al.* (2011b) Developing *Miscanthus* for bioenergy. In: *Energy Crops*. (eds Halford N G, Karp A), pp. 301–321. Royal Society of Chemistry, Cambridge, UK.

Clifton-Brown J, Schwarz KU, Hastings A (2015) History of the development of *Miscanthus* as a bioenergy crop: from small beginnings to potential realisation. *Biology and Environment: Proceedings of the Royal Irish Academy*, **115**, 1–12.

DEFRA (2007) UK biomass strategy. http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/UKBIOMASSSTRATEGY.PDF (accessed 10 November 2015). 49 p.

DEFRA (2015) *Farming Statistics – Provisional Arable Crop Areas at 1 June 2015 England*. DEFRA and National Statistics, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/453220/structure-jun2015provcrops-eng-13aug15.pdf.11 Pages. (accessed 10 November 2015).

Dohleman FG, Long SP (2009) More productive than maize in the Midwest: how does *Miscanthus* do it? *Plant Physiology*, **150**, 2104–2115.

Don A, Osborne B, Hastings A *et al.* (2012) Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy*, **4**, 372–391.

Felten D, Emmerling C (2012) Accumulation of Miscanthus-derived carbon in soils inrelation to soil depth and duration of land use under commercial farming conditions. *Journal of Plant Nutrition and Soil Science*, **175**, 661–670.

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

Hastings A, Clifton-Brown J, Wattenbach M, Mitchell P, Smith P (2009b) The development of MISCANFOR, a new *Miscanthus* crop growth model: towards more robust yield predictions under different climatic and soil conditions. *GCB Bioenergy*, **1**, 154–170.

Hastings A, Tallis MJ, Casella E *et al.* (2014) The technical potential of Great Britain to produce ligno-cellulosic biomass for bioenergy in current and future climates. *GCB Bioenergy*, **6**, 108–122.

Hansen EM, Christensen BT, Jensen LS, Kristensen K (2004) Carbon sequestration in soil beneath longterm Miscanthus plantations as determined by C-13 abundance. *Biomass & Bioenergy*, **26**, 97–105.

Heaton EA, Dohleman FG, Miguez AF *et al.* (2010) *Miscanthus*: a promising biomass crop. *Advances in Botanical Research*, **56** (56), 75–137.

Hodgson EM, Nowakowski DJ, Shield I, Riche A, Bridgwater AV, Clifton-Brown JC, Donnisona 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.

Hsu FH, Nelson CJ, Matches AG (1985) Temperature effects on germination of perennial warm-season forage grasses. *Crop Science*, **25**, 215–220.

IPCC (2014) Climate change 2014: mitigation of climate change. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, Von Stechow C, Zwickel T, Minx JC), pp. 1–30, Cambridge University Press, Cambridge, UK and New York.

Jensen E, Farrar K, Thomas-Jones S, Hastings A, Donnison I, Clifton-Brown J (2011) Characterization of flowering time diversity in *Miscanthus* species. *GCB Bioenergy*, **3**, 387–400.

Jensen E, Robson P, Norris J, Cookson A, Farrar K, Donnison I, Clifton-Brown J (2013) Flowering induction in the bioenergy grass *Miscanthus x sacchariflorus* is a quantitative short-day response, whilst delayed flowering under long days increases biomass accumulation. *Journal of Experimental Botany*, **64**, 541–552.

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.

Keane GP, Kelly J, Lordan S, Kelly K (2003) Agronomic factors affecting the yield and quality of forage maize in Ireland: effect of plastic film system and seeding rate. *Grass and Forage Science*, **58**, 362–371.

Kiesel A, Lewandowski I (2015) The effect of cutting regime and nitrogen fertilization on the quality of *Miscanthus x giganteus* biomass as biogas substrate. In: *Quo Vadis Miscanthus* (ed. Pude R). pp. 38–44. CentMa GmbH, Chartres, France.

Klimiuk E, Pokoj T, Budzynski W, Dubis B (2010) Theoretical and observed biogas production from plant biomass of different fibre contents. *Bioresource Technology*, **101**, 9527–9535.

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

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

McCalmont J, Hastings A, McNamara NP, Richter GM, Robson P, Clifton-Brown JC (2015) Environmental Costs and Benefits of Growing Miscanthus for Bioenergy in the UK. *GCB Bioenergy*. doi: 10.1111/gcbb.12294.

Meehan PG, Finnan JM, Mc Donnell KP (2013a) A comparison of the energy yield at the end user for *M. x giganteus* using two different harvesting and transport systems. *BioEnergy Research*, **6**, 813–821.

Meehan PG, Mcdonnell KP, Finnan JM (2013b) An assessment of the effect of harvest time and harvest method on biomass loss for *Miscanthus x giganteus*. *GCB Bioenergy*, **5**, 400–407.

Milner S, Holland RA, Lovett A, et al. (2016) Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *Global Change Biology Bioenergy*, **8**, 317–333.

Nishiwaki A, Sugawara K (1997) The temperature-germination rate response of *Miscanthus x sinensis* seeds. *Grassland Science*, **43**, 62–63. (in Japanese).

Nsanganwimana F, Pourrut B, Mench M, Douay F (2014) Suitability of *Miscanthus* species for managing inorganic and organic contaminated land and restoring ecosystem services. A Review. *Journal of Environmental Management*, **143**, 123–134.

Ofgem (2015) Biomass Sustainability Dataset 2013–14 https://www.ofgem.gov.uk/publications-and-updates/biomass-sustainability-dataset-2013-14. (accessed 12 November 2015).

O'Flynn MG, Finnan JM, Curley EM, Mcdonnell KP (2014) Reducing crop damage and yield loss in late harvests of *Miscanthus x giganteus*. *Soil & Tillage Research*, **140**, 8–19.

Pidlisnyuk V, Stefanovska T, Lewis EE, Erickson LE, Davis LC (2014) *Miscanthus* as a productive biofuel crop for phytoremediation. *Critical Reviews in Plant Sciences*, **33**, 1–19.

Ragoubi M, George B, Molina S, Bienaimé D, Merlin A, Hiver J-M, Dahoun A (2012) Effect of corona discharge treatment on mechanical and thermal properties of composites based on miscanthus fibres and polylactic acid or polypropylene matrix. *Composites Part A: Applied Science and Manufacturing*, **43**, 675–685.

Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: current status and future prospects. *Global Change Biology*, **12**, 2054–2076.

Smith P, Milne R, Powlson DS, Smith JU, Falloon P, Coleman K (2000) Revised estimates of the carbon mitigation potential of UK agricultural land. *Soil Use and Management*, **16**, 293–295.

Stavridou E, Hastings A, Webster R, Robson P (2016) The impact of soil salinity on the yield, composition and physiology of the bioenergy grass *Miscanthus x giganteus*. *GCB Bioenergy*, doi: 10.1111/gcbb.12351.

Sun Q, Yamada T, Takano T (2014) Salinity effects on germination, growth, photosynthesis, and ion accumulation in wild *Miscanthus x sinensis* Anderss. Populations. *Crop Science*, **54**, 2760–2771.

The Royal Society (2009) *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture*. The Royal Society, London.

Uihlein A, Ehrenberger S, Schebek L (2008) Utilisation options of renewable resources: a life cycle assessment of selected products. *Journal of Cleaner Production*, **16**, 1306–1320.

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.

Velasquez JA, Ferrando F, Farriol X, Salvado J (2003) Binderless fiberboard from steam exploded *Miscanthus x sinensis*. *Wood Science and Technology*, **37**, 269–278.

Wang SF, Wang SC, Lovett A *et al.* (2014) Significant contribution of energy crops to heat and electricity needs in Great Britain to 2050. *BioEnergy Research*, **7**, 919–926.

Webber ME (2015) A Puzzle for the Planet: our future rides on our ability to integrate Energy, Water and Food. *Scientific American*, **312**, 62–67.

Xue S, Kalinina O, Lewandowski I (2015) Present and future options for *Miscanthus* propagation and establishment. *Renewable & Sustainable Energy Reviews*, **49**, 1233–1246.

Zimmermann J, Styles D, Hastings A, Dauber J, Jones MB (2014) Assessing the impact of within crop heterogeneity ('patchiness') in young *Miscanthus x giganteus* fields on economic feasibility and soil carbon sequestration. *GCB Bioenergy*, **6**, 566–576.