Miscanspeed - accelerating Miscanthus breeding using genomic selection

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1.1 Executive summary

The transition from fossil fuels as a feedstock for alternative fuels, chemicals and materials will require a sustainable supply of biomass. Moreover, biomass crops, have the potential to sequester carbon in the soil as well as creating negative emissions if bioenergy is combined with carbon capture and storage (i.e. BECCS). Miscanthus is an ideal candidate for a UK biobased economy as it is a high yielding crop that can grow on marginal land with a low requirement for inputs and capable of energy output to input ratios in excess of 30.

Project aim: Building on over 100 years of plant breeding experience, IBERS is uniquely placed to deliver improved varieties of perennial biomass crops such as Miscanthus to meet UK targets to reduce carbon emissions. The aim of the Miscanspeed project was to accelerate the breeding of high-yielding and resilient Miscanthus varieties through the implementation of genomic selection (GS), a cutting-edge approach that leverages plant genomic information.

Background: Miscanthus, a leading perennial biomass crop, plays a key role in meeting the UK Government's legally binding commitment to achieving net zero carbon emissions by 2050. An area of 0.7 million hectares of biomass crops is required by 2050, with annual plantings of 30,000 hectares starting in the mid-2020s (CCC, 2020). Miscanthus is anticipated to represent the majority of this, based on current trends. The current Miscanthus planting area of 8,000 hectares in the UK is predominantly planted with a single hybrid clone, *Miscanthus* x *giganteus* (Mxg), which, while providing high biomass yields, presents limitations in terms of resilience and adaptability. Thus, both rapid scale up and a broader range of Miscanthus varieties are required to ensure sustainability and resilience.

Technical achievements: In Miscanspeed we achieved our dual objectives of implementing GS and speed breeding in both *Miscanthus sinensis* (Msin) and *Miscanthus sacchariflorus* (Msac), the parents of the high yielding interspecific hybrids anticipated to produce the highest yields. GS, coupled with speed breeding, offers a transformative innovation to improving Miscanthus by enhancing the speed and accuracy of breeding this perennial crop.

By reducing the Miscanthus breeding cycle from three years to one year per generation, GS enables faster genetic improvement and more efficient selection of desirable traits such as higher yield and greater environmental resilience. Furthermore, GS approaches are flexible and adaptable:

- allowing for the integration of additional germplasm and traits over time
- applicable to either clonal or seed-based products
- enabling the integration of genotype by environment (GxE) interactions with GS models to optimise multilocation trials of potential varieties prior to registration

By comparing Msin and Msac, the parental species of commercial Miscanthus hybrids, we have addressed the different biological and logistical challenges in both. We have:

- successfully achieved seed-to-seed within a single year in the UK, where little or no seed is typically produced in the first year of growth
- developed a cost-effective marker panel for all Miscanthus species to address the cost of genotyping, and this is available to the Miscanthus community

These innovations pave the way for integration of novel high throughput phenotyping techniques into GS models and facilitate the production of novel high yielding hybrids for the UK biomass supply chain.

Realising the potential of Miscanthus: The innovations developed in the Miscanspeed project will be applied directly into the Miscanthus breeding program at Aberystwyth University. We are well positioned to deliver an accelerated, flexible and effective breeding platform that supports the creation of new Miscanthus varieties for the UK and global markets. This approach will address the logistical and time/cost barriers associated with traditional breeding methods, ultimately ensuring a steady supply of Miscanthus varieties suitable for current and future climates within a meaningful timeframe. The project complements ongoing work at IBERS to develop agronomic practices and cost-reduction strategies, further enhancing the scalability and profitability of Miscanthus as a key crop in the fight against climate change and in meeting net zero targets worldwide. To achieve this, we describe business models and incentives to support the commercial uptake of Miscanthus across a range of value chains and end uses.

Summary: The Miscanspeed project has laid a strong foundation for the future of Miscanthus breeding, contributing to the UK's sustainable biomass supply and net zero carbon emissions targets. We anticipate that IBERS varieties will contribute significantly to meeting the UK’s targets for perennial biomass crops and thus contribute to negative carbon emissions via direct capture of CO_2 and displacement of fossil fuels, which can be maximised when coupled with biorefining approaches and BECCS. These industries will support a range of jobs, growth across the sustainable bioeconomy, and contribute to the wider UK economy.

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1.5 Glossary/Abbreviations/Acronyms

BBSRC	Biotechnology and Biological Sciences Research Council
BECCS	Bioenergy with Carbon capture and storage
BVCM	Biomass Value Chain Management
CCC	Climate Change Committee
CE	Controlled Environment
CPVO	Community Plant Variety Office
DEFRA	Department for Environment, Food and Rural Affairs
DESNZ	Department for Energy Security and Net Zero (Formerly BEIS)
EPSRC	Engineering & Physical Sciences Research Council
EU	European Union
GBLUP	Genomic best linear unbiased prediction
GEBV	Genomic estimated breeding value
GHG	Greenhouse Gas
GS	Genomic selection
GWAS	Genome-wide association studies
GxE	Genotype by Environment
IBERS	Institute of Biological, Environmental and Rural Sciences
JKI	Julius Kuhn Institute (Germany)

KE	Knowledge Exchange
LED	Light emitting diode
Msin	*Miscanthus sinensis*
Msac	*Miscanthus sacchariflorus*
Mxg	Miscanthus x giganteus
NERC	Natural Environment Research Council
Net Zero	The UK Government's legal commitment to reduce its net greenhouse gas emissions to zero by 2050
NZIP	Net Zero Innovation Portfolio
PBC4GGR	Perennial Biomass Crops for Greenhouse Gas Removal
SNP	Single nucleotide polymorphism
SRC	Short rotation coppice
TRL	Technology Readiness Level
UPOV	International Union for the Protection of New Varieties of Plants
XOS	Xylo-oligosaccharides
Y	Year

2. Background

2.1 Company/consortium information

Aberystwyth University (AU) in Wales was established in 1872 and since this time has developed a strong reputation for delivering academic excellence, an exceptional student experience and world-leading research.

IBERS is a renowned research institute within AU, focused on addressing global challenges such as food security, biomass, sustainability, and climate change. Based at the 160ha Gogerddan campus, and incorporating major resources including a seed biobank, the National Plant Phenotyping Centre, a grassland research platform and a pilot scale biorefining facility. IBERS research is integrated with plant breeding programs across grassland, cereals and bio-energy crops (Figure 1). Our vision is 'To carry out research to ensure that humanity can sustainably produce the food, feed and plant based industrial resources it needs'.

Figure 1 The IBERS Ecosystem

2.2 Project background

The aim of the Miscanspeed project was to develop and implement GS to accelerate the breeding of high yielding, resilient Miscanthus varieties for the UK.

UK biomass demand outstrips domestic supply, making us dependent on imports which are under increasingly competitive demand. If we are to meet the UK's legally binding commitments under the Climate Change Act (2008), domestic biomass supply is expected to play a key role in providing feedstock for Biomass Energy with Carbon Capture and Storage (BECCS), which is required to deliver 63% of the UK's annual negative emissions by 2040 (CCC, 2020). Domestic production would have significant economic and environmental benefits beyond decarbonisation.

Whilst in the short term, moderate increases in planted area could be met by clonally propagated material, significant and rapid expansion will require novel technologies and crop diversity, including seed-based hybrids, both to meet the volumes of planting material required, and to limit the resilience risks that would result from reliance on a small number of clones as the UK's climate changes.

With the future likelihood of rapid increases in demand, accelerated genomic breeding is the only technology to offer a step change in the speed of delivery of new Miscanthus varieties to meet the market need for planting materials at the scale needed, diversity of varieties, improved resilience traits and higher yield.

3. Project Overview

3.1. Aims and objectives

The aim of Phase 2 of the Miscanspeed project was to develop and apply GS in accelerating the breeding of high yielding, resilient Miscanthus varieties for the UK. Miscanthus takes three years to mature in the UK. Implementation of GS in Miscanthus breeding should reduce each generation of the breeding cycle from three years to one, helping to deliver an effective and flexible breeding platform for the future to rapidly deliver commercial varieties.

To do this, the objectives were:

- To collect genomic marker and phenotype data from two Miscanthus populations to train and test/calibrate GS models to predict traits of interest.
- To perform annual seed to seed cycles (speed breeding) within each population.

3.2 Schedule, deliverables, and financial information

The Miscanspeed project comprised seven work packages. In addition to Project Management and Governance, technical components were Field Trials, Genomic marker development, Genomic Selection, Speed breeding and Southern latitude crossing. The Knowledge exchange and commercialisation work package involved the creation and implementation of a knowledge transfer plan, including a website (http://www.miscanthusbreeding.org/miscanspeed.html) and publicity materials, as well as the generation of reports on the impact of breeding and social value, and commercialisation report.

The technical schedule was largely determined by the annual Miscanthus cycle. In Y1, deliverables included phenotyping and development of markers for the training set (90 Msin and 335 Msac genotypes, planted in single replication breeder's trials in Germany) to generate GS models, as well as crossing the training set parents to generate the C0 population. Subsequent years involved annual optimisation of the speed breeding conditions and annual crossing and genomic selection of progeny (Figure 2). The training set was dug in Y1 following phenotyping and established as a replicated trial at Aberystwyth for re-phenotyping in Y3.

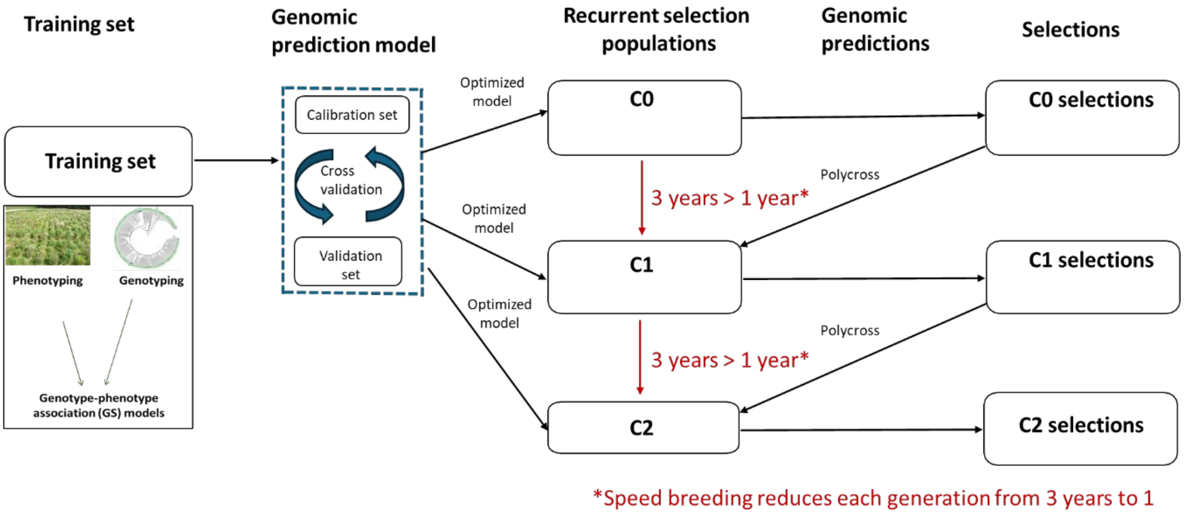

Figure 2 Graphical overview of the Miscanspeed project

Additional components of Miscanspeed included development of the commercial framework for the Miscanspeed innovation (Section 5) and regular stakeholder engagement (Section 6).

Progress was evidenced via regular technical and financial reporting, stage gate reviews, and site visits by DESNZ. Bi-annual financial claims and evidence were submitted to DESNZ, the total funds allocated to the project over the three years was £2,083,720.88.

4. Technical requirements

4.1 The design and development of the innovation

4.1.1 State of the art at project initiation:

Approximately 8,000ha Miscanthus was growing in the UK, the majority of which was *Miscanthus* x *giganteus* clone 'Illinois' (Mxg), a sterile triploid between parental species Msin and Msac. While this has excellent yield potential, it is limited by cold and drought. Additionally, if we are to upscale Miscanthus production to meet the demand specified by the CCC, it is important to diversify the crop to avoid a monoculture of a single clone.

IBERS has bred the first ever Miscanthus varieties to receive Central Plant Variety Office, Europe(CPVO) registration as biomass crops (Appendix 1), all other Miscanthus varieties registered by breeders have been ornamental. Following multi-location trials, these varieties are licensed for multiplication and commercial sale to Terravesta, who are in the later stages of scaling up propagule production in order to bring the varieties to market. The aim of Miscanspeed Phase 2 at initiation, was to develop the technological innovations required to accelerate the development of subsequent varieties.

Breeding strategies.

The IBERS breeding program is based on an extensive collection of Miscanthus species, primarily Msin and Msac, and including others such as *M. lutarioparius*, *M.robustus* and *M. floridulus*. These are evaluated for:

- Performance (yield)
- Ability to form fertile seed
- Performance of the progeny

An individual with excellent performance might be considered for commercialisation directly, as occurred with Mxg and a small number of other clones. However, in the longer term, plant breeding is required to increase yield, extend the geo-climatic zones over which the crop can be planted and to increase the diversity within the crop.

There are two main breeding strategies in Miscanthus:

1. Paired crossing – involving two parents. Resulting progeny are 'full siblings'. The first generation is called the 'F1' and may demonstrate heterosis, more commonly referred to as hybrid vigour, particularly if the parents are genetically distant from one another. This approach produced the 7 registered IBERS varieties.
2. Population breeding – involving multiple parents. Seed from a single plant will be 'half siblings' with pollen donated from several parents. This approach produced the two recurrent selection populations (Msin and Msac) used in the Miscanspeed project.

In either case, the resulting progeny are evaluated and the best selected for subsequent crossing. Evaluating progeny is time consuming and laborious, requiring the establishment and phenotyping of field trials. Miscanthus does not mature for 3 years in the UK and if clonal replicates are required, this will add at least an additional year to the timeframe for each generation. Breeding typically comprises of multiple generations of crossing and selection. Application of GS, coupled with speed breeding, will reduce the timeframe for each generation to 1 year.

The best performing types are ultimately sent on for multilocation trialling to ensure robust performance prior to sending them for variety registration and scale-up for commercial sale.

Speed breeding in Miscanthus

In conventional breeding, Miscanthus plants would typically only be crossed once mature, which can take up to 3 years in the field in the UK. In common with other crops, Miscanthus genotypes have been observed to flower more synchronously and more prolifically when grown at lower latitude sites, closer to the equator. To achieve seed-to-seed in a single year the plants were therefore sent south to grow and flower more rapidly. The state of the art at the beginning of the project was to mimic the day length and temperature profiles of lower latitude sites in glasshouses in the UK. This enabled crosses to be made between a wider range of genotypes. However, these were largely limited to those genotypes in which flowering synchronised, rather than desirable crosses. Furthermore, seed set was lower in the glasshouse than in the field.

Biomass crop resources

In parallel with the breeding program outlined above, IBERS researchers have worked extensively on understanding the traits underpinning biomass accumulation (e.g. Robson *et al.*, 2013) and analysed the molecular regulation of these traits, both by transcriptional (De Vega *et al.*, 2021b) and genome-wide association studies (GWAS, Slavov *et al.*, 2014). Extensive multilocation trials have been conducted and the limits to growth modelled (Lewandowski *et al.*, 2016; Awty-Carroll *et al.*, 2023). The genomes of Msin and Msac had been sequenced (Mitros *et al.*, 2020; De Vega *et al.*, 2021a). The theoretical basis for GS in Miscanthus had been established (Slavov *et al.*, 2014, Davey *et al.*, 2017, Slavov *et al.*, 2019), but not yet implemented.

Agronomy and production

While breeding can increase the yield potential of the crop, the actual yield realised is dependent on the environment. As a perennial crop, Miscanthus requires different agronomy to conventional annual crops. Furthermore, the establishment costs are significant, with return on investment delayed until at least year 2. Decreasing propagation and establishment costs, and maximising establishment and early growth are therefore important components required to de-risk and avoid some of the limitations of Miscanthus.

Much work has been done to optimise and compare scale up technologies, including the generation of hybrid seed at commercial scale and extensive work to optimise and reduce the cost of plug plant production and planting.

Miscanthus may be planted either clonally or by seed. Current Miscanthus varieties are clonal and are typically planted as rhizomes. Alternative options include stem propagation and tissue culture propagation. Clonal propagation is the only method available for sterile hybrids such as Mxg but may also be selected for very high yielding individuals, or for scale up of parents for F1 hybrid generation.

- **Clonal propagation from rhizome** has limited capacity for scale up as it involves a time delay while the plant grows, and destruction of the original plant.
- **Stem propagation** has greater scale up potential as each node up the stem can theoretically become a new plant, and a single plant can be harvested for stems for several years as this approach does not involve digging up the rhizome. However, stem propagation is highly dependent on the genotype, with some being amenable and others unable to clonally reproduce in this way.
- **Tissue culture** provides the most scalable route to rapid production of clonal plants. Hundreds or thousands of plantlets can be generated for large scale plantings. There may be a phenotypic imprint of tissue culture on the crop for

many years, so it will be important to evaluate plant performance taking into account the propagation method.

- **Seed propagation**, either from paired or population crosses, is in its infancy but has many advantages to the industry. Miscanthus seed is not yet directly drilled but established as plug plants and planted in the same way that tissue cultured plantlets would be. Seed offers great scalability, and most importantly, results in a genetically diverse crop where each seed is unique, minimising the risks associated with monocultures.

Appropriate agronomy has been developed for Miscanthus to ensure robust establishment and to reduce costs where possible. State of the art methodology includes the application of mulch film at planting and is under study as part of the PBC4GGR project, whose aim is to demonstrate the role of perennial biomass crops in meeting the UK's net zero carbon objectives.

4.1.2 Miscanspeed Innovation

Genomic Selection

In Miscanspeed the aim was to implement GS in Miscanthus for the first time. The primary advantage of GS is to reduce the time taken to evaluate the progeny at each generation by using predictions based on genetic marker information at the seedling stage as opposed to awaiting the mature phenotypes.

GS requires a training set with robust phenotype data and an appropriate marker set. These data are combined in a genomic selection model, and this is then used to rank the progeny based on the marker information alone, reducing the timeframe from 3 to 1 years per generation. Ultimately, we are interested in generating interspecific 'Mxg type' hybrids as these have been demonstrated to have the highest biomass yields.

In selecting a training set, there are various factors to consider, each of which can affect prediction accuracy. Population size and genetic diversity of the training population, genetic relationship (kinship) and population structure of the training population with the breeding population, and quality of the phenotypic data applied in the statistical models are features connected with training population and should be optimized. Density and distribution of genetic markers across chromosomes, level of linkage disequilibrium between QTL alleles and marker alleles, genetic complexity and heritability of target traits, applied statistical methods, and non-additive genetic factors such as genotype-by-environment (G×E) interactions hugely affect the final output of the GP accuracy. Unfortunately, the time taken for Miscanthus to mature limited the options available to the following two populations.

At the start of the Miscanspeed project, recurrent selection populations of Msin and Msac were growing in the field at the Julius Kühn-Institut Federal Research Centre for Cultivated Plants, Germany (JKI). They consisted of 90 Msin and 335 Msac genotypes, planted in single replication trials. These populations were selected as training sets because they were populations from within Miscanthus genetic groups, which facilitates the marker analysis and they were known to flower sufficiently synchronously, which is important in order to generate sufficient seed to establish the next generation.

An additional trial of ~1000 Miscanthus genotypes including Msin, Msac, other species and interspecific hybrids was discussed but deemed to be too complex. To determine whether GS could be applied to a Miscanthus breeding program, the decision was made to use the Msin and Msac recurrent selection populations as these represent the major genetic groups of interest. Although we effectively doubled the work by using both groups, it was determined that it was important to gain the understanding in both species, especially as the future aim is to apply GS in interspecific hybrids.

Speed breeding

In conventional breeding, Miscanthus plants would typically only be crossed once mature, which can take up to 3 years in the field in the UK. The implementation of GS and reducing the seed-to-seed time to a single season necessitates rapid maturation and seed set, summarised as 'speed breeding'. To achieve seed-to-seed in a single year the plants were sent south to grow and flower more rapidly. The site chosen was El Hierro in the Canary Islands, off the coast of Morocco (Figure 3).

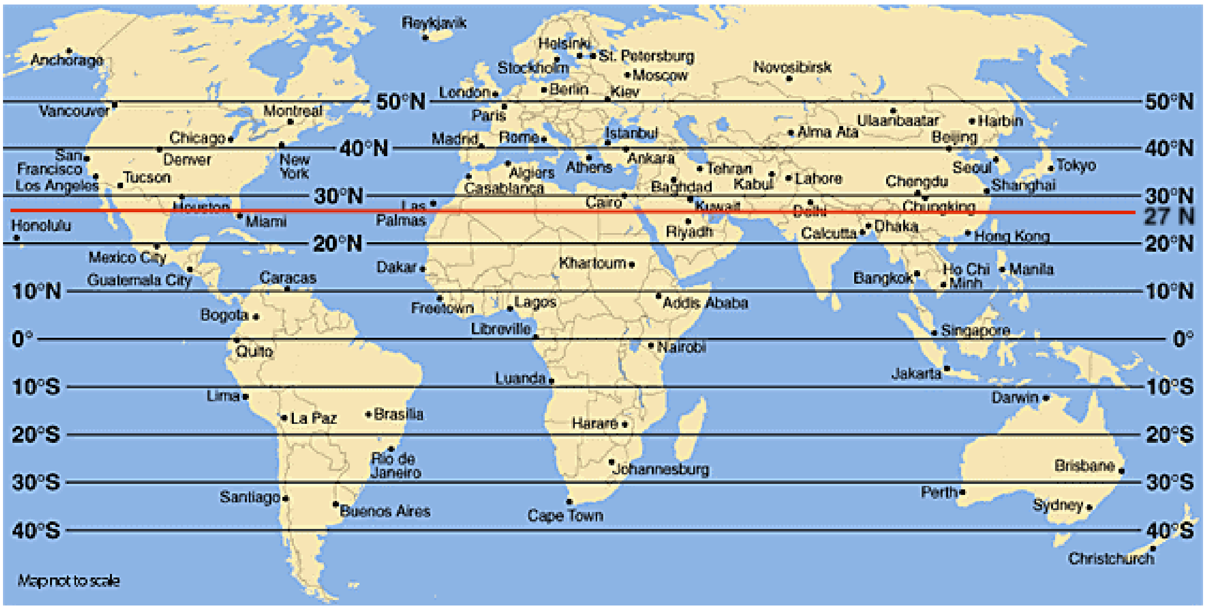

Figure 3 27.7°N latitude (red line), where El Hierro island is located

Key features of the southern crossing site:

1. **27.7°N latitude is perfect for crossing Miscanthus.** This latitude provides a "breeding sweet spot" for flowering synchronisation among most of IBERS' germplasm collection, including Msin and Msac. Achieving flowering synchronisation between Miscanthus species is one of the most challenging aspects of Miscanthus breeding and is difficult to manipulate naturally.
2. **Elevation Diversity for Breeding Experiments:** El Hierro offers extraordinary elevation variation, allowing the same crosses to be tested at different altitudes, from sea level to 1,500 meters above sea level, all within a 30-minute drive. This

is invaluable for observing plants' responses to varying heat exposure, humidity, and cloud cover (solar radiation) within a fixed photoperiod.

3. **Strategic Importance for Northern Europe:** The southern latitude is crucial for developing interspecific hybrids dedicated to Northern Europe. Moreover, crosses made in southern latitudes often do not produce viable seeds in northern climates above 45°N latitude.

The southern crossing location served two important purposes. Firstly, to achieve the annual seed-to-seed cycle required to implement GS and secondly to inform the environmental conditions for the speed breeding in Aberystwyth.

Speed Breeding involved customizing glasshouses to modulate temperature, humidity, and lighting, and monitoring the impact of conditions on growth and flowering over three years. It involved isolating parent plants, adjusting growth dynamically, synchronising flowering, crossing, and collecting seed during years 1, 2, and 3. Meteorological data was captured from two locations at different altitudes on El Hierro throughout the project and used to program bespoke glasshouse facilities at IBERS to accelerate plant development, synchronise flowering and optimise seed set within a single growing season. Specific modifications implemented to achieve this include: slow-release fertiliser mixed into the growth medium; an automatic irrigation system, with backup irrigation controlled by water probes in the soil; Philips top lights producing efficient light wavelengths for optimal growth; Kroptech intra-canopy lighting to allow greater light interception into the canopy of larger plants, ducting pipe for cooling and ventilation, a chiller unit and insulated copper piping to cool belowground with respect to ambient air temperature (Figure 4).

4.1.3 Progress made during Miscanspeed

From a technology readiness level (TRL) of 4 (technology validated in lab) at the start of the project, the TRL level advanced to TRL 5 (technology validated in relevant environment) and achieved the expected TRL 6 (technology demonstrated in relevant environment) by the end of the project for both GS and speed breeding. An advantage of the innovations developed in Miscanspeed is that they can be implemented incrementally into the breeding program. For example, the marker data can be used to select parents for crossing, with or without incorporating GS at each generation and speed breeding techniques can increase the number of crosses that can be made, regardless of how the parents are selected.

Figure 4 Customised glasshouse for speed breeding Miscanthus

Our GS innovation is expected to reach TRL 9 (technology prototype demonstration in an operational environment) by 2026. To reach TRL 9 in the GS innovation would require us to develop a dedicated GS model for inter-specific hybrids. To reach TRL 9 for speed breeding would require investment in larger scale bespoke glasshouses enabling a higher number of crosses to be undertaken to provide a larger number of inter-specific hybrids to be produced to select from. This in turn would maximise the likelihood of identifying highly productive hybrids for trialling. However, the innovation can be implemented using the infrastructure developed within Miscanspeed.

Any hybrids performing well when transferred into the field environment would then undergo multi-location trials prior to (or possibly in parallel with) licensing. Building on the innovations developed within Miscanspeed, we will be able to further accelerate the phenotypic validation and multi-location trialling stages using a novel GS method called Sparse Testing (see section 8), thereby further reducing the time required to develop the next varieties for protection and deployment.

4.2 Demonstration and results

We had two key performance metrics, aligned with our aims:

1. Calibration and validation of the GS models
2. Quantify the improvement in flowering synchrony and seed set in responsive controlled environments (CE) in the UK

4.2.1 Msin and Msac training sets and test sets.

GS training sets are used to establish GS models for application in a separate population, the test set. Training sets must be sufficiently related to the test set for the models to be relevant in terms of their genetic relatedness. The Msin and Msac test sets were generated by re-crossing the parents of the Msin and Msac training sets respectively, to generate the first generation (C0) of the test set populations (Figure 2). The test sets were therefore siblings to the training sets, ensuring the GS models would contain all the necessary information to enable predictions on the test sets.

Phenotyping was completed on the Msin and Msac training set populations in Y1, autumn 2022 (peak yield) and spring 2023 (harvest), when the plants were 2 years old. Breeding populations were evaluated from breeder's plots sited in Germany as Miscanthus reaches maturity faster under the continental climate than in the UK. Biomass yield and other important traits were measured for each species (Figure 5).

Leaf samples were taken for DNA extraction and marker development. Msin and Msac training set rhizomes were harvested from JKI and established at Aberystwyth using an incomplete block design with four replications. In Y3 of the project the plants completed their second growing season in Aberystwyth and were re-phenotyped to compare with the JKI data. Autumn phenotyping was completed (2024) with the spring phenotyping to be completed in spring 2025. The phenotype data will be analysed for correlation in trait rank order between the two environments.

4.2.2 Developing and implementing Miscanspeed GS models.

The ability to perform GS requires routine genotyping at a high number of loci across the genome. Single nucleotide polymorphisms (SNPs) differentiate individuals based on variations detected at the level of a single nucleotide base in the genome. SNPs have become the marker of choice for crop genetics and breeding applications because of their high abundance in genomes, and the availability of a wide array of genotyping platforms with various multiplex capabilities for SNP analysis. Marker development was performed by LGC (previously Rapid Genomics) in two stages. Firstly, CaptureSeq was used to generate thousands of *de novo* markers across the Miscanthus genome. These were then combined with existing markers from out 1000 plant ABR33 diversity trial and the combined set screened for representation across the genomes of Msin and Msac. A robust FlexSeq panel of 11,000 loci was generated (7,659 CaptureSeq loci, 3,341 loci the ABR33 SNPs). A total of 41,903 high quality single nucleotide polymorphisms (SNPs) were identified at the 11,000 loci in the combined Msin and Msac training sets, and this is available as a cost-effective marker panel to make this technology more accessible.

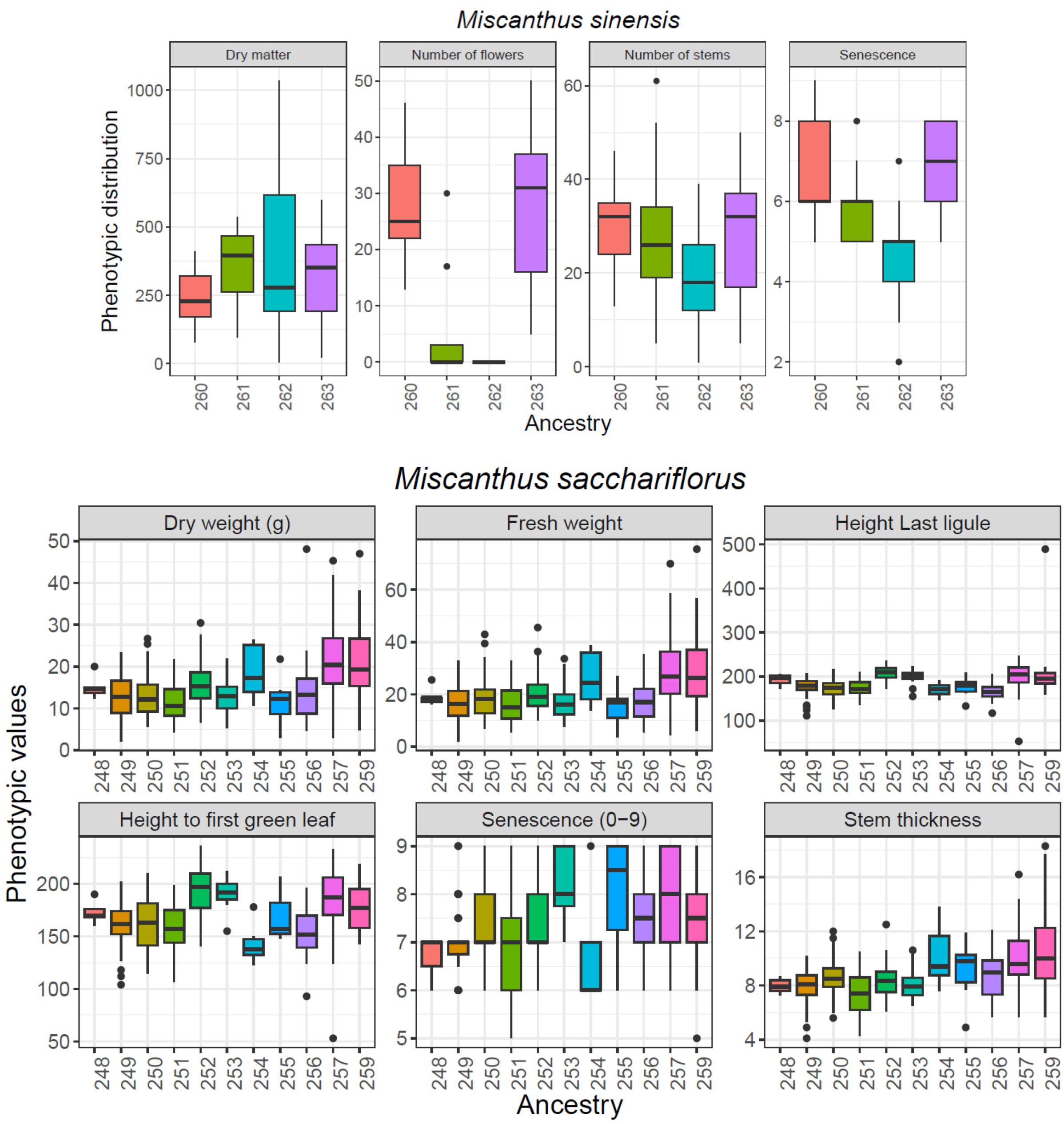

Figure 5 Boxplots of Y1 phenotype measurements taken from the training sets A. *Miscanthus sinensis* B. *Miscanthus sacchariflorus*

A cost-benefit analysis was performed and indicated that the trend in predictive abilities and heritability were similar across all eight traits. Predictive ability was low at marker density of 1,363 and reached a plateau at 10,904 for all the traits. A marker density of 10,904 was sufficient for accurate prediction on the breeding value for all the traits in the studied Miscanthus population (Figure 6). Using a lower marker density of ~11,000 significantly reduces the cost of genotyping whilst maintaining the predictive ability in Miscanthus breeding program.

Phenotypic and genotypic (marker) data from the two training sets (90 Msin, 335 Msac) were combined to generate GS models for the two species. The predictive ability of 6 commonly used GS models were evaluated from the training set data. All the six models had almost similar predictive ability i.e. ~0.43 for Msac and ~0.25 for

Msin. Genomic Best Linear Unbiased Prediction (GBLUP) model was selected to estimate breeding values for the C0 and C1 populations.

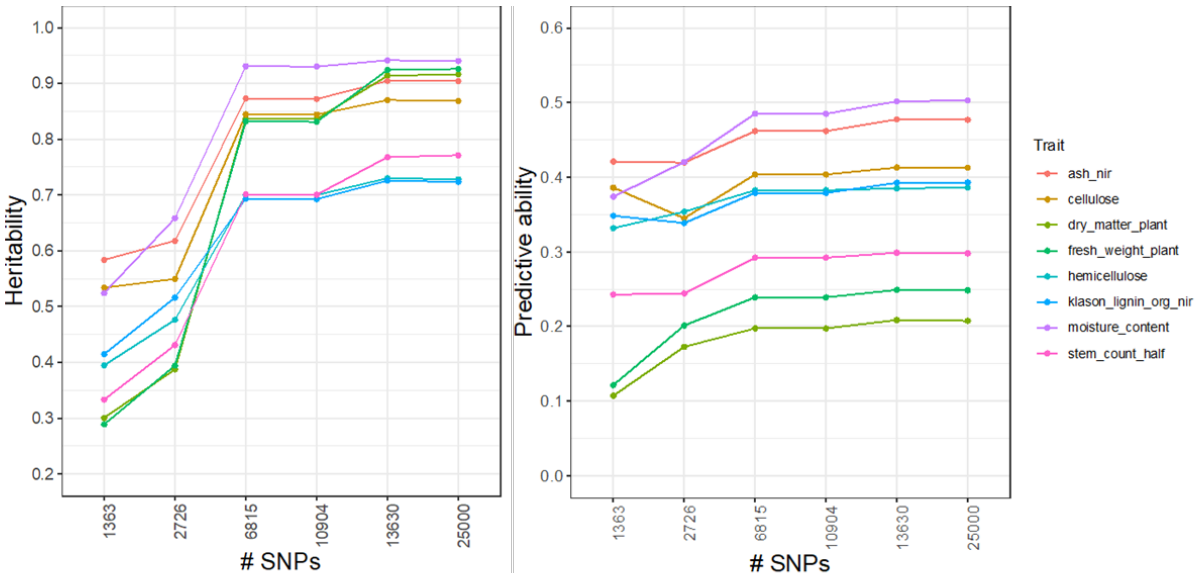

Figure 6 The estimated heritability (A) and mean predictive ability (B) of cross-validation for genomic prediction of eight traits under different marker densities.

Following re-crossing of the training set parent plants, the GS models were then used to predict and rank the performance of the C0 and C1 populations at the seedling stage, based on marker data alone, to avoid having to wait for three years for the plants to reach phenotypic maturity. A total of 20 genotypes with high breeding values for dry matter were selected as parents for the next crossing cycle in each of the two recurrent selection populations.

The C0 seedling population was genotyped for a total of 160,196 SNPs. A total of 21,023 common SNPs were selected between the C0 population and the training population. The 21,023 common SNPs were used in the prediction model to predict the C0 seedling population. Similarly, the C1 population (developed from the C0 population) was genotyped for 11,126 SNPs. A total of 3,028 common SNPs between the training set and C1 population were selected. The 3,028 SNPs were used for predicting the C1 populations.

GS models were developed for all measured traits, however GS was implemented based on biomass yield alone. Y3 phenotyping of all traits in the field in Aberystwyth will enable a comparison of the rank orders for all traits.

Genomic estimated breeding values (GEBVs) of the training set and the seedling populations (C0 and C1)

Genomic estimated breeding values (GEBVs) of the Msin and Msac training set and the C0 and C1 seedling populations were generated (Figure 7) and ranked. The top 20 genotypes were selected as parents for the subsequent generation.

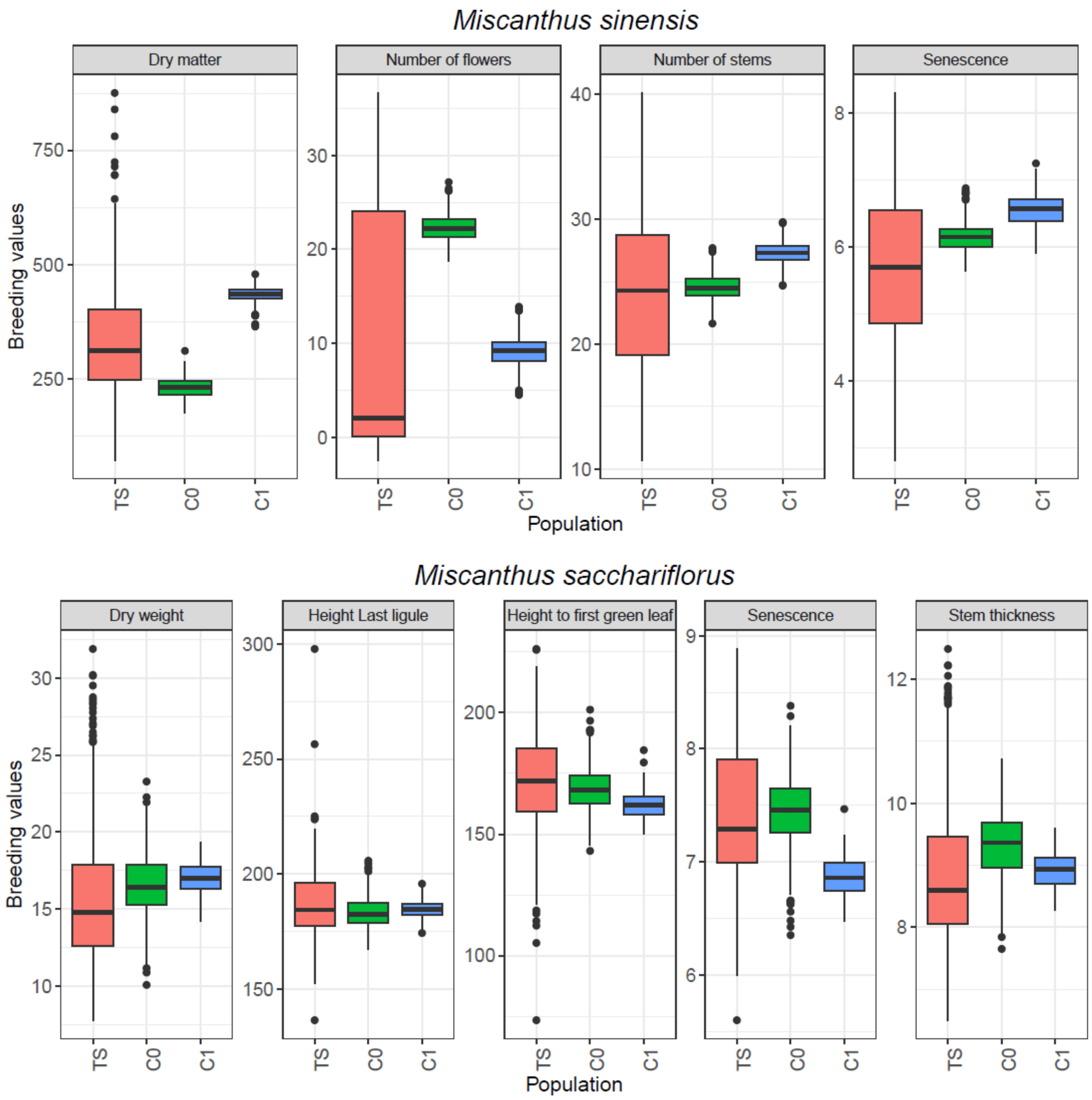

Figure 7 Genomic estimated breeding values (GEBVs) of the training set and the seedling populations (C0, C1) for *Miscanthus sinensis* and *Miscanthus sacchariflorus*

4.2.3 Use of a southern latitude site for crossing and seed generation

To generate the C0 populations, the parents of the Msin and Msac training set populations were sent to our Southern crossing location (located on the 27th parallel North) run by Energene Seeds Ltd. and planted in crossing blocks (Figures 8 and 9).

Flowering time data for each plant and meteorological data were collected (details below). Seed were harvested and brought to Aberystwyth for marker analysis and GS. Selected progeny were returned to the Southern crossing site for subsequent rounds of crossing and seed set.

The unique conditions of the southern latitude crossing site have been used as a benchmark for setting up the conditions for speed breeding at IBERS.

4.2.4 Development of speed breeding in the UK

1. Comparison of flowering times in Aberystwyth and the southern crossing site

In Y1 the existing CE facilities were set to mimic the day length and temperature profiles of lower latitude sites where Miscanthus was known to flower. Concurrently, we developed the modifications of the compartments for application in Y2 and Y3.

Y1 Comparison of flowering in unmodified CE and the low latitude site: In year Y1 the parents of the Msin and Msac training set populations were grown from rhizome in CE. Temperature and lighting period were set to simulate the southern crossing sites managed by Energene Seeds Ltd., and environmental data were recorded throughout the experiment. Flowering stages (categorised 1-4, from initiation to full flowering) and length of every stem (culm) were measured from each plant during the flowering assessment period. All flowering stages were recorded for the Msin recurrent population, and most plants flowered, whereas the Msac population only achieved stage 1 (flag leaf visible but no panicle exerted) and most plants showed no signs of flowering.

Figure 8 *Miscanthus sinensis* (right) and *Miscanthus sacchariflorus* (left) selections potted up at the southern crossing site

Figure 9 *Miscanthus sinensis* selections planted in a crossing block at the southern crossing site

The same genotypes were cloned and grown in a crossing block at the southern crossing site (Figure 9). Flowering phenotypes were assessed from all plants and meteorological data was recorded throughout. Flowering of genotypes grown at the southern crossing site was more extensive and all genotypes flowered.

Accumulated degree days was estimated for the CE-grown Msin plants with a base temperature of 10 °C. Plants in CE achieved flag leaf stage with an accumulated degree day value of 1114 to 1412. There was a remarkable general similarity in the number of degree days accumulated in the equivalent Msin plants growing at the southern crossing site, which flowered between an accumulated 1189 to1447 degree days.

Flowering in the Msac population was more difficult to achieve in Aberystwyth. For the induction of flowering in the Msac population, we may assume some other condition critical to flowering has not been duplicated in the glasshouse. Conditions other than photoperiod or temperature may be limiting growth of the Msac plants, e.g. nutrient and water availability or light quantity and quality.

Lessons learned in Y1: Both populations were observed to be weak, leading us to the conclusion that greater light, temperature, soil volume, and nutritional inputs should be provided to generate larger plants capable of supporting greater seed production and or completion of growth. Additionally, the lack of progress beyond flag leaf stage in Msac plants suggested the growth environment lacked either the precise photoperiodic signal required to induce flowering, or that the plants had not achieved the necessary vegetative growth to complete flowering, potentially due to insufficient thermal units.

All flowering stems that achieved anthesis (pollen release) were either the longest or the two longest stems recorded on the plant. Plants that achieved anthesis produced seed, therefore there appeared to be no intrinsic barrier to fertility and seed production in the modified growth rooms, although as anticipated the overall seed production was low. Our results indicated that the growth of long stems should be prioritised over many stems.

2. Developing bespoke environments to control phenology in Msin and Msac

The proposed modifications to the existing CE glasshouses were to achieve:

- flowering in plants grown from seed within one season
- high seed set in plants grown from seed within one season

In addition to light and temperature which were controlled in Y1, additional factors were considered:

Light quality: To maximise light input we used combinations of LEDs above the canopy and as intra-canopy lighting to maximise biomass accumulation.

Substrate and nutrition: The general availability of nutrients was increased, along with substrate volume, to allow larger root mass to sustain more flowering stems.

Humidity: Vapour-pressure deficit (the amount of moisture in the air/the amount of moisture the air can hold when it is saturated) was managed through regulation of air humidity to a level that did not approach either extreme.

Year 2 Comparison of flowering in modified CE and the southern latitude site

Selections from the recreated C0 of the Msin and Msac recurrent selection populations were grown in customised CE and at the southern latitude crossing site, with the aim of achieving seed-to-seed within one growth season. Temperatures in the CE were broadly similar to those at the southern crossing site (Table 1) and followed a day night cycle to approximate that expected in the natural environment.

Table 1 The means of Y2 summer temperatures (°C) in controlled environment (CE) at Aberystwyth and at the southern crossing site

	CE, Aberystwyth	Southern crossing site
Msin	22.9	21.9
Msac	23.9	

In addition to the regulation of air temperature within the CE, a chilling treatment was applied to the substrate to simulate the differential in temperature experienced by the above and below-ground parts of the plant in the field, and to determine whether this might provide a mechanism by which to modulate phenology (Msin only).

The success of the customisations applied to the Msin population in Y2 can be summarised (Table 2):

Table 2 Summary of Msin phenology under unmodified CE, modified CE and southern latitude crossing site conditions.

Msin	Y1	Y2		
	Unmodified CE	Control (ambient)	Cooled substrate	Southern crossing site
Number of plants		4	4	20
Stem numbers		37	36.3	
Mean stem length (cm)		139.8	103.3	
Flowering stems/plant (total)	1.2 ± 0.2	6.75 ± 1.2 (31)	4.25 ± 2.2 (14)	
Seed set		Over 1300 (across both treatments)		900

1. Good vegetative growth and significant stem numbers were achieved from seed within a single growth season.
2. There was a significant increase in flowering between Y1 (unmodified) and Y2 (customised). The plants in Y1 were established from rhizome which typically would be expected to produce more rapid growth than plants established from seed, however that was not the case.
3. Over 1300 seeds were produced from the six Msin plants that flowered in the customised CE. Only 900 seed were produced from the Msin population plants at the southern crossing site, despite there being twice as many plants in the crossing block.
4. Chilling reduced the number of flowering stems and delayed flowering.

Following analysis of Y1 data for Msac, targets for Y2 included increasing plant biomass and stem elongation. We were successful in increasing average stem numbers on Msac plants (from 7.1 in Y1 to 160.0 in Y2), however, the plants were largely prostrate, which is not typical in the field. Three Msac plants achieved flag leaf later in the year, but these stems did not progress to produce fertile flowers.

Lessons learned in Y2:

The lower seed set from plants at the southern crossing site in year 2, was attributed to strong winds. Subsequent crossing blocks were better protected from the prevailing wind and performed better.

Our observations through the Msin growth season suggested that the initial cooling temperature was too low and caused stress allowing some biotic infection to develop in the plants. In Y3, a second iteration tested supplemental UV light which should assist in reducing the potential impacts of biotic stress.

We hypothesised that the Msac prostrate growth habit was due to the light conditions. We added Infra-red LEDs to the light during the Y2 growth season, as plants are highly sensitive to the ratio of red to far-red light and initiate a shade avoidance response when more far-red light is detected. Some qualitative improvements in habit were noted (stems were more upright). However, the impacts were minimal as most of the growth season was completed without the supplemental lighting.

Year 3 Flowering and seed set in modified CE

Final modifications were completed, including the addition of far-red light for the Msac population. Both populations achieved anthesis. For the first time we demonstrated large scale flower production in Msac growing in CE, with all plants completing flowering (Figure 10, Table 3). Seed production was assessed once panicles had ripened, beginning in December. Panicles were harvested from 7 Msin and & 7 Msac plants, and a subset were sown directly onto sand to assess fertile seed. The Msin plants produced approximately 3300 seed, a great improvement on the 1000 produced in Y2. The Msac produced around 430 seed, where previously no seed had been produced prior to the modification to the growing conditions.

4.2.5 Summary of progress towards our key performance metrics

1. Calibration and validation of the GS models

Early prediction of mature crop phenotypes is a major aim for plant breeders. However, while many traits contributing to yield in Miscanthus have high heritability (genetic contribution to the trait), biomass yield has a relatively low heritability, indicating that it is highly impacted by the environment over the perennial lifecycle of the crop, limiting the usefulness of predictions based on seedling phenotype. In Y1, the time taken to develop the markers prior to their application necessitated a phenotypic selection of the C0 population, based on seedling vigour, with GS rankings following once the markers were available. As anticipated, the seedling vigour did not correlate well with the GS ranking, confirming our assumptions, and the necessity for a GS approach.

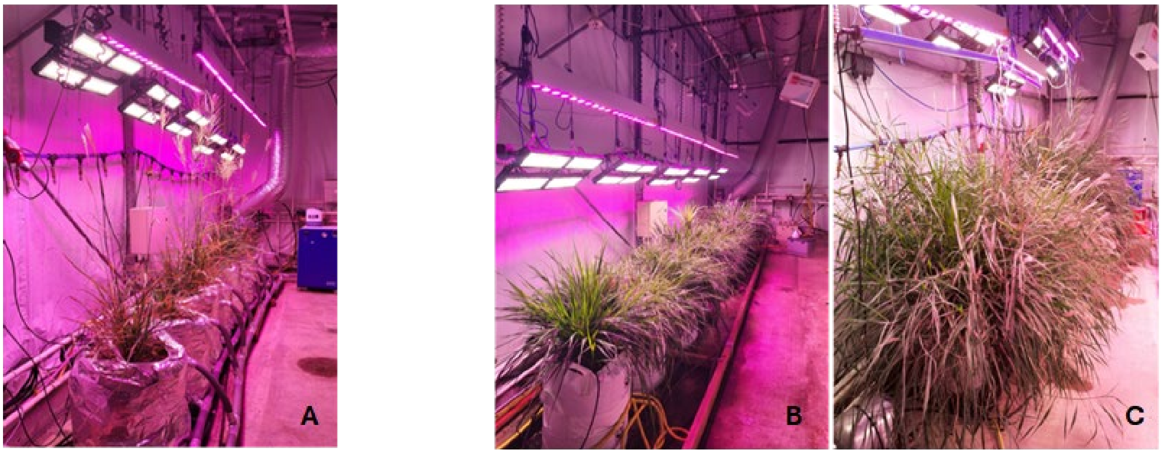

Figure 10 Progress in speed breeding in Miscanthus during the Miscanspeed project. A: Msin, Y2; B: Msac, Y2; C: Msac, Y3.

In Y2, GS was used to make the selections, thereby demonstrating its application in Msin and Msac for the first time. Seedlings are growing for Y3 marker analysis and GS rankings. Yield predictions for Msin and Msac C0 and C1 populations indicate that GS has resulted in improved biomass yield in both species (Figure 11).

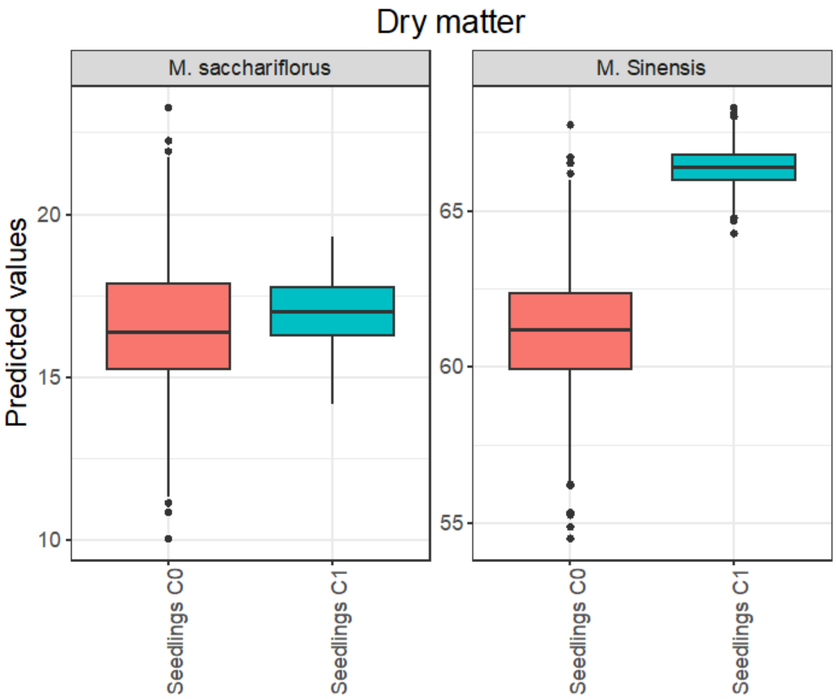

Figure 11 Boxplot of predicted C0 and C1 seedlings population.

2. Quantify the improvement in flowering synchrony and seed set in responsive controlled environments in the UK

We have demonstrated for the first time that CE alone can produce sufficient seed from Msin to facilitate GS and we have achieved flowering in the more challenging species, Msac (Table 3 and Figure 10).

4.3 How, and to what extent, the innovation contributes to increasing sustainable UK biomass supply.

To date, only Mxg has been grown extensively, with Terravesta also planting clone 'Athena' (3,000ha to date). Existing IBERS varieties are currently being scaled up for release from 2026.

Table 3 Summary of progress in speed breeding in Msin and Msac during the Miscanspeed project

	M. sinensis	***M. sacchariflorus***
Y1	*Unimproved growth environment* Flowering a few tens of seeds	*Unimproved growth environment* No flowering
Y2	*with improvements* 33 flowering panicles on 8 plants ~2000 seed produced	*with improvements* Significant vegetative growth, 1-2 flag leaves
Y3	*Temperature* Significant flowering difference – can regulate flowering to make hybrids	*Additional FR LEDs* Significant flowering Hoping for good seed set

In Miscanspeed, we have demonstrated that GS, coupled with speed breeding, can be achieved in Miscanthus species Msin and Msac. By implementing GS and speed breeding innovations and integrating these with additional innovation under development to apply GS to the multilocation trial phase (Sparse Testing, see section 8), we anticipate more rapid release of new varieties with higher yields and improved resilience. This will provide more choice to growers, including in areas currently unsuitable for Miscanthus cropping, and in turn ensure a more robust supply of domestic Miscanthus biomass, with all the concurrent environmental benefits of growing the crop.

Using the innovations developed in Miscanspeed we can more rapidly develop Miscanthus varieties to address environmental challenges, and we will be able to breed increasingly for carbon sequestration and other environmental traits beyond yield, e.g.

- Miscanthus is a perennial crop, with no damaging annual ploughing cycle, and accumulates carbon in the soil via roots, rhizomes and litter drop.
- Using Miscanthus grown on-farm can offset the need to buy in straw or alternative bedding material, reducing competition for national biomass supplies and reducing transportation costs and emissions.
- Using Miscanthus biomass for building materials sequesters the carbon for at least the lifetime of the building, and longer if circular economy principles are applied.
- Coupling heat and power generation from biomass, including Miscanthus, with BECCS results in negative carbon emissions and long-term greenhouse gas reductions.

- Benefits to soil health include root penetration of deep soils. Miscanthus tolerates waterlogging and is ideal for wetlands adjacent to rivers or streams to reduce flooding risk.
- Miscanthus may be planted as buffer strips to minimise soil and nutrient runoff from field and into watercourses.
- The crop stands over winter and can physically trap debris from floods, reducing damage downstream.

Ultimately, growers will decide where to plant Miscanthus. This is likely to avoid competition for food crops which will attract higher prices and maximise benefit to the farmers, e.g. via valorising lower grade land, increasing self-sufficiency and maximising environmental benefits to the farmland.

In all cases, ensuring that growers have the choice of varieties to provide maximum economic and environmental benefit in their location is critical. It is therefore essential to breed new high-yielding and resilient Miscanthus varieties for the current and future UK climates. This will involve pulling together all our expertise on Miscanthus trait biology, our diverse genotype collection and our innovations in breeding methodology. The next stage is to apply this innovation to high-yielding interspecific hybrids.

4.4. Key successes

In Miscanspeed we have:

- developed a cost-effective marker panel for all Miscanthus species available to the Miscanthus community
- successfully implemented GS in Miscanthus species Msin and Msac for the first time.
- achieved seed-to-seed within a single year, at scale, within the UK, where little or no seed is typically produced in the first year of growth.
- developed Sparse Testing, integrating GxE interactions with GS, to innovate the next stage of the breeding cycle, multilocation trialling
- paved the way for integration of novel high throughput phenotyping techniques into GS models (Figure 12).

4.5 Persistent barriers:

While Miscanspeed has been successful in achieving its original and additional objectives, it is important to highlight challenges. By comparing the implementation of GS and speed breeding in both Msin and Msac we have identified differences in the two species, confirming the need to address both species rather than assuming that knowledge from one will automatically apply to the other.

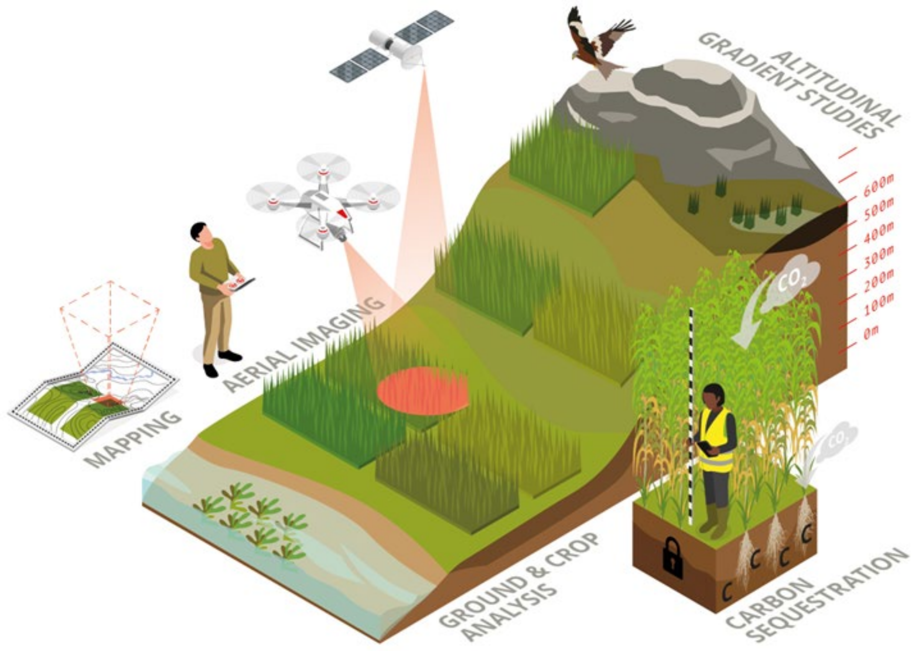

Figure 12 Integration of novel phenotyping techniques and genotype x environment analyses into future breeding for climate resilient crops with novel traits including carbon sequestration

As a novel crop species with a large, complex genome, there are relatively few genomic resources for the crop, although this is improving rapidly. The highest quality reference genome for Miscanthus is Msin (Mitros *et al.*, 2020) with chromosome assemblies available for Msac (de Vega *et al.*, 2021a) and other species. This could have resulted in lower quality markers for Msac. Additionally, transferability of data from one trial to another is hindered by the use of different genomic markers as the technologies have developed over time. Although many people are now employing skim-seq (low coverage whole genome sequencing) this is not appropriate for GS as the computational analysis is time consuming and the shallow coverage does not result in easily comparable markers across individuals. To address both issues, we opted to develop a robust, cost-effective marker panel, applicable to all Miscanthus species, and incorporating previous markers as well as new ones to maximise the interoperability of the panel for current and future use. The Flex-seq markers provide markers at fixed locations across the genome which enable rapid marker analysis to be performed. This resource is now available to the community. Despite optimisation, marker cost remains a barrier to the uptake of GS in plant breeding programs.

Although Msin was the smaller of the two initial training populations, Msac has consistently been more challenging in terms of flowering synchrony and seed set. While marker technology and novel bioinformatic pipelines can accelerate GS, speed breeding is challenging biological limits in Miscanthus. We have made great progress in achieving seed set within a year in both Msin and Msac, with excellent seed set obtained in Msin. However, despite the huge advance achieved via the introduction of infra-red lighting, it remains to be seen whether Msac seed set is sufficient for large scale deployment of annual selection cycles.

4.6 The impact of the innovation on Greenhouse Gas emissions.

Actual GHG emissions savings from biomass crops are dependent on biomass yield, area planted and the rate of uptake as well as end use.

The aims of the Miscanthus breeding program at IBERS are to develop new varieties with high yields and resilience to climatic challenges in order to maximise both the yield per hectare planted, and the geographic area over which Miscanthus might profitably be grown. Figure 13 (reproduced from Hastings *et al.*, 2009) shows the potential for increases in both yield and potential area over which Miscanthus might be grown, with respect to the standard Mxg clone. The innovations developed in the Miscanspeed project will accelerate the development of new varieties, and thereby enable more rapid uptake.

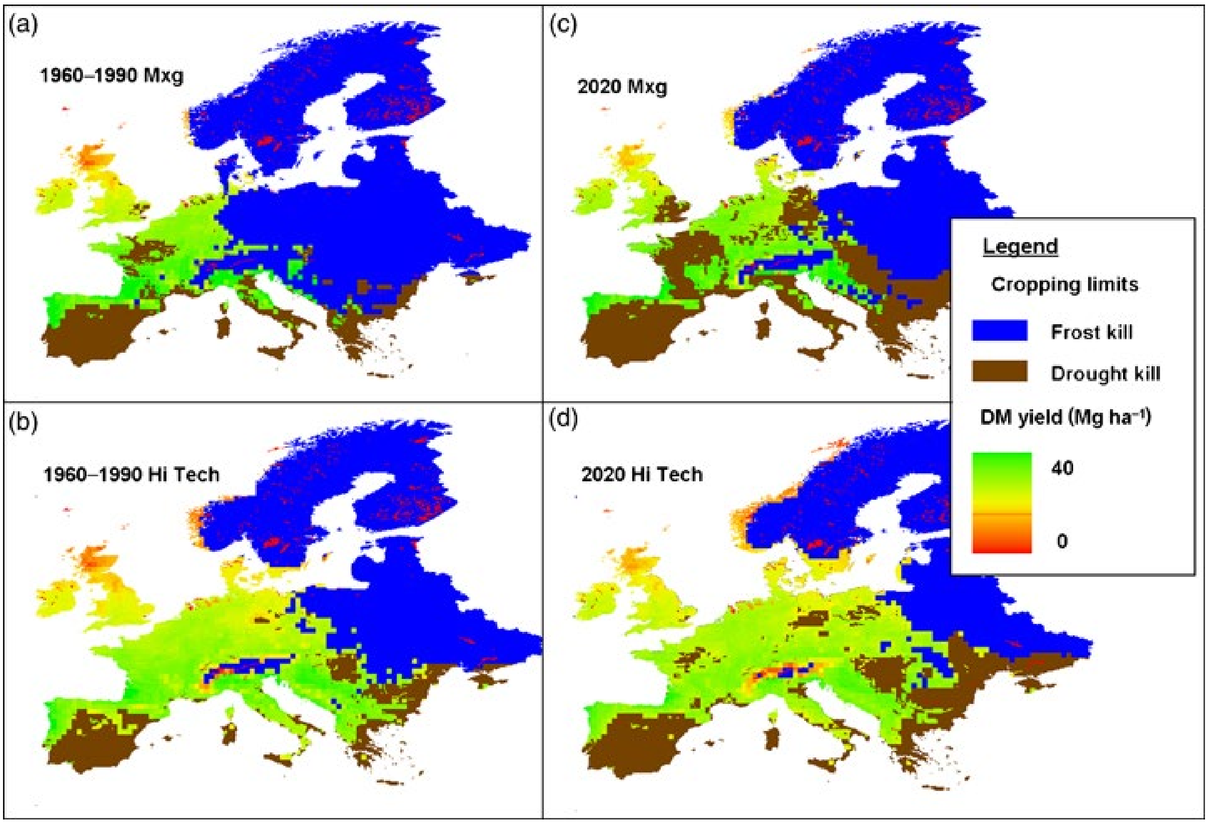

Figure 13 *Miscanthus* × *giganteus* and Miscanthus 'hi-tech hybrid' mean peak dry matter yields for the Intergovernmental Panel on Climate Change A2 scenario time slices shown with a frost and drought kill mask of one event per 15 years for 1960–1990 and 2020, Frost kill is shown in blue and drought kill in brown. Mxg (a) 1960–1990, (c) 2020, hi-tech hybrid (b) 1960–1990, (d) 2020. Reproduced from Hastings *et al.*, 2009.

The CCC (2020) indicate that 0.7 million hectares of biomass crops is required by 2050, with annual plantings of 30,000 hectares starting in the mid-2020s. Miscanthus is anticipated to represent the majority of this, based on current trends. The percentage of Mxg planted will decrease over time with higher yielding IBERS varieties set to contribute at least half of Miscanthus plantings in the UK by 2050, based on market shares of our current crops.

A Miscanthus plantation can be carbon neutral without increasing soil carbon stocks (Robertson *et al.*, 2017), however carbon savings may be greater where Miscanthus is grown on former arable land than grassland, where existing carbon stocks are higher. (McCalmont *et al.*, 2015). New, higher yielding varieties may also offer higher Cseq potential. In all cases, Miscanthus should be used using circular economy guidelines, to ensure maximum carbon reduction benefits.

New high-yielding and resilient Miscanthus varieties will capture CO_2 directly from the air and convert it to biomass both above and below ground.

- Belowground roots, rhizomes and leaf litter will contribute to soil carbon pools and improve soil quality, potentially decreasing other GHG emissions such as N_20.
- Aboveground biomass will be harvested and used to displace fossil fuel use in heat and power generation, which, coupled with BECCS is a carbon negative technology.
- Use of biomass to generate transport fuels will also displace fossil fuel use.
- Local use of Miscanthus e.g. for animal bedding, will reduce transport of other straws across the UK.
- Other uses, such as in building materials or biochar, will lock up carbon for long periods of time.
- Finally, Miscanthus biomass can be converted in biorefineries to chemicals and products currently based on fossil fuels.

A peer-reviewed publication on the benefits, challenges, and trade-offs of upscaling Miscanthus production in the United Kingdom was published in 2024 to provide the evidence base required by policy makers (Hodgson *et al.*, 2024, Figure 14).

4.7 Lessons learned

In Y1 we brought together a new team to deliver Miscanspeed. The project was designed robustly with inbuilt risk- mitigation, e.g. the doubling of work to run both Msin and Msac was important to ensure the project was not dependent on a single population, and we have learned far more about the challenges in both species, the similarities and differences between the two species, and how to synchronise their flowering to move towards hybrid breeding as a result.

In Y1, we implemented best practice for Miscanthus plant husbandry, however the project also required new protocols to be developed. All protocols and experiences were reviewed following the first year and modified to ensure all lessons learned were implemented to optimise quality assurance in subsequent years e.g. smarter plant labelling, optimised timing of seed establishment and leaf sampling to ensure marker analysis was completed in time to run GS models and make selections.

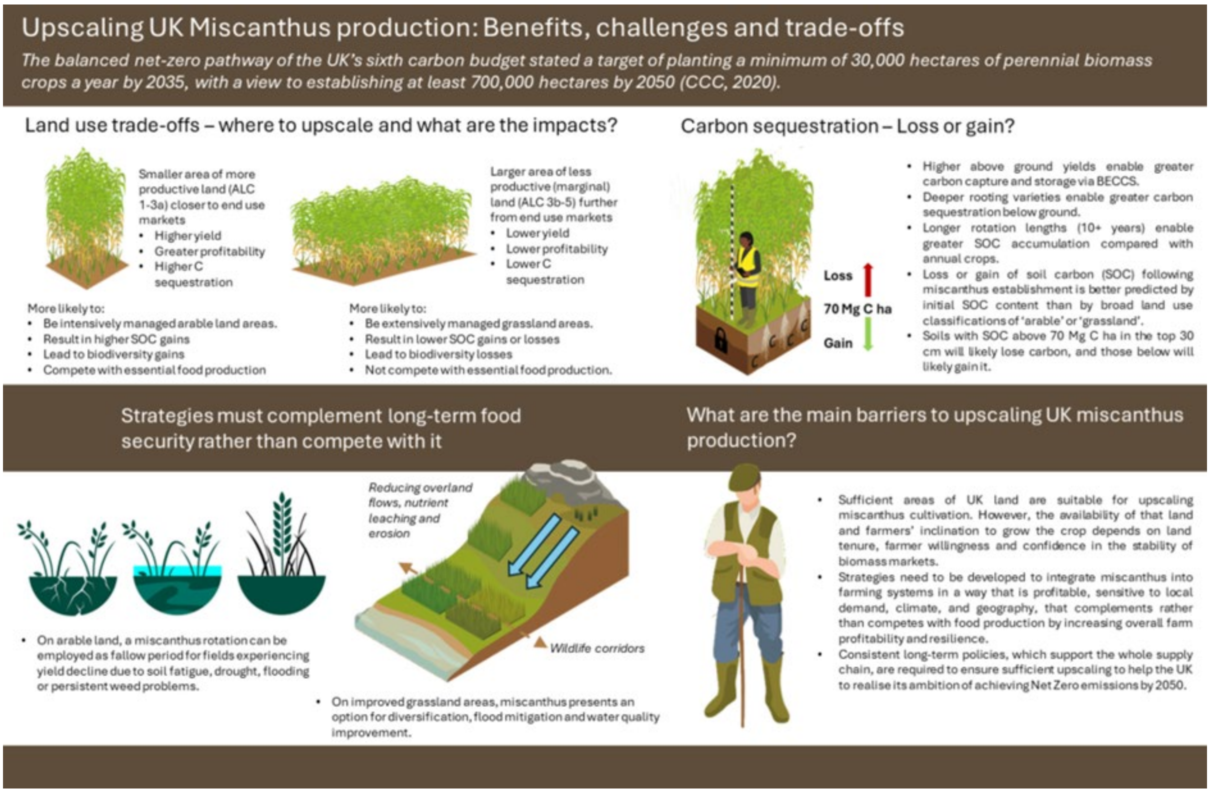

Figure 14 Graphical abstract for Upscaling Miscanthus production in the United Kingdom: The benefits, challenges, and trade-offs (Hodgson *et al.*, 2024)

It was important for all parties to meet regularly and discuss all aspects of the project to integrate the multiple components effectively. The risk register was updated to reflect additional risk mitigations implemented.

We have learned that it is possible to implement GS in Msin and Msac. The time taken to develop markers was problematic in Y1, but importantly, application of the markers in subsequent years was feasible. This however is dependent on optimising each stage of the process: seedling establishment, plant growth, accelerated flowering time, seed harvest, germination, leaf sampling, DNA extraction, marker analysis, and GS ranking. To this end, a universal and cost-effective marker set has been developed, following a marker number analysis to reduce costs while maintaining predictive power. The next stage is to integrate additional innovations in phenotyping and GxE studies (Figure 12) and apply this innovation to high-yielding interspecific hybrids.

We have developed bespoke glasshouse facilities to enable speed breeding of Msin and Msac in the UK. This has involved building on previous knowledge about the regulation of phenology in the two species and implementing appropriate modifications for each.

5. Commercialisation Plans

The UK's transition to net-zero emissions by 2050 necessitates expanding biomass crops to 700,000 ha, of which Miscanthus should constitute the majority. Miscanthus, recognized for its high biomass yield, high energy yield potential, low input requirements and adaptability to marginal lands, is an ideal candidate for biomass production, addressing the growing demand for sustainable feedstock. A Miscanthus crop covering 600,000 ha could provide up to 3 million tonnes of oil equivalent (Mtoe) annually, providing approximately 55-60% of the UK's residential electricity needs at 2022 levels. Currently, the UK has around 8,000 hectares of Miscanthus, with plans to expand significantly (DEFRA Survey of Agriculture and Horticulture 2021). IBERS have registered the first novel biomass varieties of Miscanthus to address this anticipated market demand.

The key to commercial success lies in prioritising traits such as biomass yield and drought resistance, enabling the development of varieties that thrive under challenging conditions, thus opening new markets. Genomic selection reduces breeding cycle times and costs. Collaborative partnerships with genomics companies can drive technological innovation, while licensing and royalties from proprietary varieties generate revenue. Overall, the strategic integration of genomic technologies into Miscanthus breeding can boost commercial viability whilst supporting global efforts toward sustainable development and climate change mitigation.

Our Miscanthus assets can be summarised as:

a. the breeding programme itself and associated germplasm and expertise
b. GS models
c. existing plant variety rights held and potential future varieties

The assets we can commercialise are Miscanthus varieties, and GS is a key innovation to accelerate and enhance our ability to produce new varieties. As such, the commercial landscape for these varieties is the main consideration in developing our commercialisation plan, with the understanding that the earliest date by which we could expect a new variety to be licenced from Miscanspeed innovation would be 2030. Following selection within a breeding program, it is essential to evaluate the selections of interest in multilocation trials to ensure they perform across a range of environments before they are sent to CPVO for evaluation.

At this stage we envisage the primary route for IBERS to benefit from commercialisation of our varieties is via royalty payments (as we do for oats and forage grasses). Whilst for most plants royalty payments are based on seed sales, as a perennial crop, royalties based on tonnes harvested is a more suitable model for Miscanthus. Whether future varieties are licenced on an exclusive or non-exclusive basis will be determined based on market maturity, number of companies operating in the market, and the market readiness of the variety. At present, the scale and maturity of the market is insufficient for joint venture to be attractive to investors, but this remains under consideration for specific markets (e.g. varieties developed for specific climate zones, or with properties tailored to specific end market uses).

Commercial applications for Miscanthus biomass

The Biomass Strategy (2023) set out a clear path for the potential end uses for biomass in the short, medium and longer term. We have used it to inform our thinking regarding research on end uses, and in our interactions with end user industries (e.g. ongoing discussions with Drax and Tata Steel about the scope for Miscanthus to meet some of their fuel demand and help them align with net zero objectives).

Miscanthus is a renewable source of biomass. It can be chipped, baled, or processed into pellets for improved storage, transport and usage. Miscanthus biomass has many end uses including:

Energy Miscanthus is used in power stations for electricity, and in combined heat and power plants on farms to heat buildings. There are 226 Biomass plants in the UK, with an installed capacity of 1.58GW (UK Electricity Production). It can also be used in domestic wood burners and open fires.

BECCS The use of Miscanthus for Bioenergy with Carbon Capture and Storage provides the maximum benefit in terms of GHG savings.

Transport fuels Miscanthus can be converted into ethanol for blending with petrol.

Animal bedding Miscanthus is used as bedding for horses and livestock. It can be finely chopped and spread under wheat straw. In addition to providing farmers with an on-farm source for personal use, there are a number of companies in the UK selling Miscanthus bedding products.

Biochar Miscanthus can be pyrolised to biochar for soil amendment, locking up the carbon for long-term storage. The Miscanthus biochar value chain was reviewed in 2021, it was concluded that Miscanthus biochar application benefits soil health, and that biochar production is relevant for phytoremediation and a zero-waste approach, with pyrolysis conditions and application rate being important considerations (Pidlisnyuk *et al.*, 2021).

Biocomposites: Miscanthus can be used to make biodegradable plastics and fibres. Biocomposites can replace conventional construction materials, which can cause environmental damage and biodiversity loss. Examples include:

- **Building materials:** Miscanthus can be used in light concrete, wall and wind-protection covering, loam walls, insulation, and roofing.
- **Car parts:** Miscanthus can be used in steering wheels and as an oil binder.
- Horticulture: Miscanthus can be used in pots, culture substrates, mulch, and bedding for fruits and vegetables.
- **Food packaging:** Aim to replace the 2 billion plastic food trays with biobased alternatives, including Miscanthus (e.g. KCC Packaging).

High value products: Case Study 1- Xylitol production from Miscanthus

Xylitol is an alternative sweetener to sugar and xylitol has been recognized by the US Department of Energy (DOE) as one of the top 12 value-added chemicals obtained from biomass (Werpy *et al.*, 2004). The xylitol market size is estimated at $1.11billion in 2025, expected to reach $1.43billion by 2030 (Mordor Intelligence). ARCITEKBIO, a spinout from AU, has developed a robust biomanufacturing solution to produce xylitol from a range of agricultural sources, including crude Miscanthus.

Integrated biorefinery: Case study 2. Alternative Miscanthus value chains

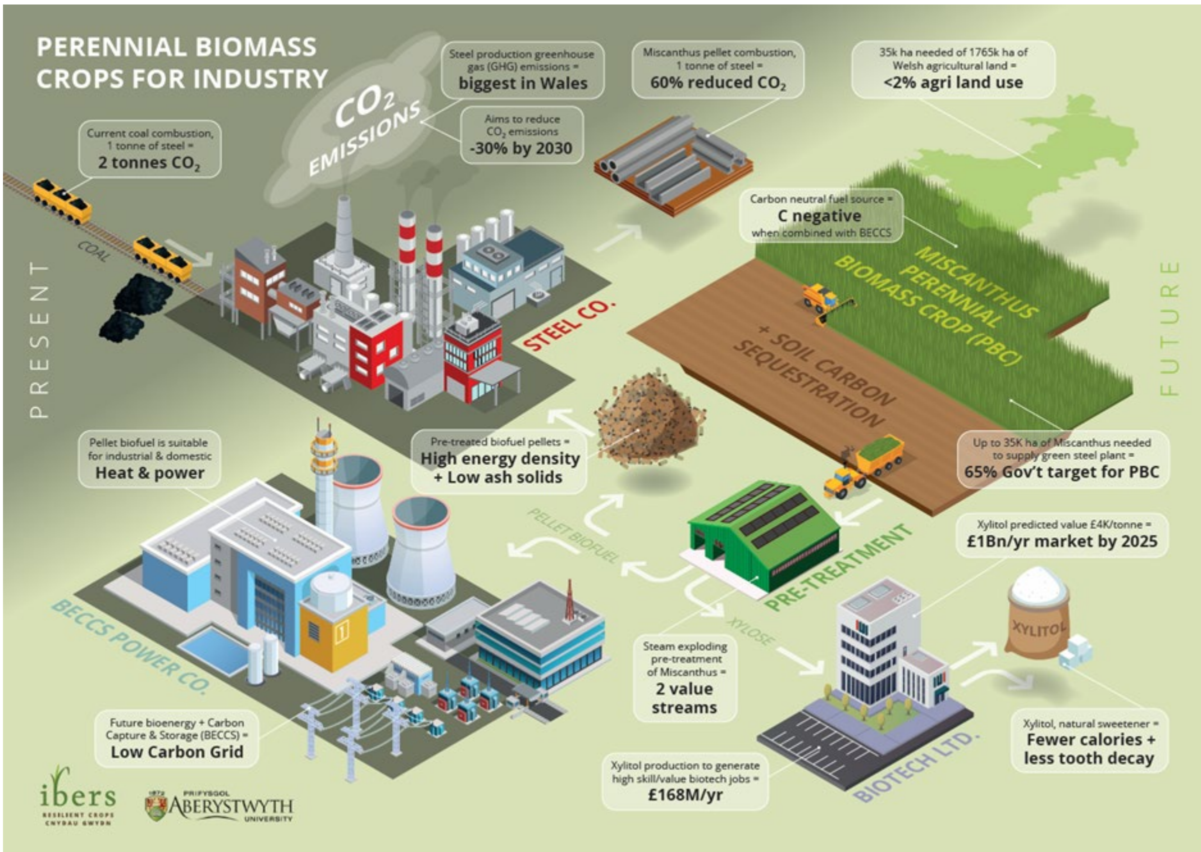

Figure 15 An integrated value chain for Miscanthus incorporating BECCS, high value product extraction, and heavy industry applications

End uses considered include heat and power coupled with BECCS, extraction of xylo-oligosaaccharides for high value products, and high calorific value pellet production for use in furnaces (Figure 15). Components of this scenario are being tested in the Biotechnology and Biological Sciences Research Council (BBSRC) Follow on Fund project ‘Miscanthus to Xylo-oligosaccharides and Biocarbon - Innovating Feed, Food and Steel Industries (MAXFEED)’. The project aims to unlock the full potential of Miscanthus as a sustainable source of bio-based products (XOS and bioenergy) paving the way for a more resilient, circular and environmentally responsible future.

While yield and resilience remain the key traits for growers, it is possible to breed for additional traits, including those for specific end uses. Although the mulifunctionality of the crop is currently seen as a benefit, in the future there may be demand for targeted varieties. Using Miscanspeed innovation it will be possible to accelerate the selection of specific desired traits.

5.1 Scalability and applicability to other sites

Now that we have demonstrated GS in Miscanthus, these innovations, developed in Miscanspeed, will accelerate the development of new high yielding Miscanthus varieties. Additional traits can now be incorporated using these innovations, to breed for different environments and end uses, as the market demands, and thereby future proofing the Miscanthus industry against any emerging threats. As our understanding of relevant marker-trait associations improves, we can more rapidly incorporate this knowledge into Miscanthus breeding programmes.

Conducting a comprehensive market analysis is essential to identify the most promising geographic markets and sectors, which can inform product development strategies. A well-defined strategy ensures that the breeding program aligns with market demands and capitalizes on emerging opportunities.

Once a new variety has been developed and registered, the next challenge is to produce sufficient rhizome or seed for commercial planting. Whilst seed based varieties carry a number of advantages, it is likely that clonal varieties will continue to play a role in the Miscanthus market, particularly in the short to medium term. Clones provide uniformity, and since they are typically planted from rhizomes, they are potentially more suited to sites with more difficult land (e.g. weed burden, soil type, spring temperatures). Commercial scale Miscanthus seed production will not be undertaken in the UK owing to its latitude and climate. In common with other crops, large scale crossing blocks will be established at a southern latitude for maximum seed production (Figure 16). These seed will then be distributed and marketed. In other projects, IBERS continues to develop agronomic protocols for seed-based varieties, given the much higher potential multiplication rates that are possible, and the other advantages of seed-based varieties.

In either case, the approaches developed in Miscanspeed are relevant to the development of both seed and clonal varieties, including sterile triploid hybrids which could be deployed in areas where the climate might otherwise favour flowering and seed set.

5.2 Access to revenue support mechanisms

As Miscanthus is a novel crop entering novel value chains, it is important to address all components simultaneously if we are to realise the benefits of this valuable carbon reduction technology.

Ultimately, the industry will need to be demand-driven and economically sustainable. However, there may be need for incentivisation in the early years if the UK is to realise the ambitions laid out by the CCC and achieve its carbon targets (see Appendix 2).

Figure 16 Commercial scale Miscanthus seed production in Southern Spain

5.2.1 Plant Breeding

To date, Miscanthus breeding and the associated science at IBERS has been funded by the public sector via Defra, BBSRC, EPSRC, Innovate-UK, NERC, and EU as well as private investment (UK Plant Science Research Strategy 2021, Appendix 3). We anticipate that Miscanthus breeding will remain in the public sector for the foreseeable future, with private income generated in the form of royalties. The potential for revenue is currently limited by the uptake of Miscanthus by farmers, which has been identified as the major barrier to the development of the Miscanthus industry in the UK.

Breeders and research institutions play a pivotal role in the development of new Miscanthus varieties. They require revenue support mechanisms to sustain research and development (R&D) activities, which are often capital-intensive and long-term. Some key mechanisms include:

Grants and Public Funding: Governments and public institutions often provide grants to support agricultural research. These funds can help breeders cover the costs of developing new Miscanthus varieties, which can take years to perfect.

Institutions can also access funding from international bodies focused on climate change and renewable energy, given Miscanthus's role in carbon sequestration and bioenergy.

Intellectual Property (IP) Rights: Licensing agreements and royalties from patented Miscanthus varieties can provide breeders with a steady revenue stream. Protecting intellectual property ensures breeders can recoup their R&D investments.

Collaborative Ventures: Partnerships with private companies can lead to shared R&D costs and risks. These collaborations can provide breeders with additional resources and access to market channels.

Licensing and Royalties: Current IBERS varieties are licensed to Terravesta who are responsible for marketing and sales.

Our aim is to continue to develop proprietary Miscanthus varieties with desirable traits and to license them to appropriate agricultural companies or growers. Securing intellectual property, e.g. via Plant Breeder's Rights (PBR) ensures compliance with national and international laws such as the International Union for the Protection of New Varieties of Plants (UPOV) to protect plant varieties and facilitates earning royalties from each sale or use of your varieties. Licences should define the Scope of Use, the Territorial Limits, and Exclusivity (where applicable).

5.2.2 Seeds and Rhizomes Nurseries

Nurseries that specialize in Miscanthus seeds and rhizomes are critical for the supply chain, ensuring farmers have access to high-quality planting material. Revenue support mechanisms for nurseries include:

Certification Programs: Certification for quality assurance can command higher prices and build trust with farmers and institutions.

License: Partnering with research institutions for exclusive rights to new plant varieties can create additional revenue.

Cooperative model: Cooperative models between seed producers and rhizome nurseries can enhance service delivery to multiple Bioenergy Value Chain Management (BVCM) systems. By pooling resources, these cooperatives can ensure a steady supply of quality planting materials, share infrastructure, and reduce costs. Additionally, they can coordinate research and development efforts to improve plant varieties and cultivation techniques. The cooperative approach can also help in lobbying for better policy support and accessing larger markets collectively.

5.2.3 Farmers and Farmers' Organizations

Farmers are essential to the Miscanthus value chain, providing the raw biomass. Miscanthus companies state establishment costs to be around £1,889/ha (2023 prices, Terravesta), with return on investment delayed for two to three years while the crop establishes. It is therefore important to develop specific revenue support mechanisms to enable growers to make the investment to grow environmentally sustainable biomass crops.

Subsidies and Incentives: Government subsidies for growing energy crops can make Miscanthus cultivation an attractive option for farmers. Incentives for sustainable farming practices can also support farmers transitioning from traditional crops to Miscanthus.

Access to Finance: Loans with favourable terms for purchasing seeds, rhizomes, and necessary equipment are vital. Financial support from cooperatives or farmers' organizations can also reduce individual risk.

Offsetting costs such as animal bedding: Miscanthus biomass can be an effective way to offset costs in various agricultural applications. When used as animal bedding, Miscanthus provides excellent absorbency and comfort for livestock, which can lead to healthier animals. Additionally, its use can reduce dependency on traditional bedding materials such as straw or wood shavings, which can be more expensive or less sustainable. Miscanthus biomass can be composted after use, further contributing to a closed-loop system on the farm.

Direct revenue from biomass sales: currently ~£100/ton'

Long-term contracts with buyers: Long-term contracts between Miscanthus growers and end-users such as power stations and high-value product developers, provide the stability required for both parties. For power stations, long-term contracts ensure a consistent supply of Miscanthus biomass, which is crucial for maintaining operational efficiency and meeting renewable energy targets. This predictability allows power stations to plan their energy production and manage costs more effectively. Moreover, suppliers benefit from guaranteed sales over an extended period, which can facilitate investment in cultivation, processing, and logistics. Additionally, committing to a long-term supply can lead to better pricing structures and reduced volatility compared to spot contracts, where prices can fluctuate widely based on market demand and supply conditions.

Robust supply chains providing sufficient demand: A robust supply chain is crucial for ensuring sufficient demand for Miscanthus biomass. This involves establishing a seamless network from production to end-user, which can stimulate both demand and supply effectively. If farmers are assured a reliable market for Miscanthus, they are more likely to invest in its cultivation. Simultaneously, if industries recognize the benefits and availability of Miscanthus biomass, they are more likely to incorporate it into their operations. Developing strong partnerships, investing in processing facilities, and ensuring consistent quality are key strategies to reinforce the Miscanthus supply chain. This approach can help transition Miscanthus from a niche product to a mainstream agricultural commodity, thereby balancing both sides of the market equation and ensuring long-term sustainability.

Cooperative Models: Farmers can form cooperatives to pool resources, share risks, and increase bargaining power with processors and end users. Cooperatives can also facilitate access to shared equipment and infrastructure, reducing individual costs.

Carbon Credits: Farmers can earn additional income by participating in carbon credit programs, capitalizing on Miscanthus's carbon sequestration abilities.

5.2.4 Biomass Value Chain Management (BVCM) Companies

BVCM companies are responsible for the logistics and processing of Miscanthus biomass, turning raw material into usable products. Their revenue support mechanisms might include:

Investment and Financing: Access to investment from venture capitalists or green investment funds is crucial for scaling operations. These funds are often interested in sustainable and renewable projects. Loans and credit lines from banks, specifically tailored for bioenergy projects, can provide necessary capital.

Government Incentives: Tax breaks, subsidies, and other incentives for renewable energy projects can significantly impact the financial viability of BVCM companies. Policies supporting biomass as a renewable energy source can help stabilize markets and provide clear revenue forecasts.

Market Development and Contracts: Long-term contracts with end users, such as power generators, can provide a predictable revenue stream and justify investment in infrastructure. Developing new markets for high-value products can diversify revenue sources and reduce dependency on any single end user.

Carbon Credits: By participating in carbon credit markets, BVCM companies can enhance their revenue through the sale of credits earned from the carbon offsetting attributes of Miscanthus biomass.

5.2.5 End Users: Power Generators and High-Value Product Generators

End users are the final link in the value chain, utilizing Miscanthus biomass for energy production or as raw material for high-value products. Their revenue support mechanisms include:

Energy Policy and Tariffs: Feed-in tariffs and renewable energy certificates can provide power generators with a premium price for electricity generated from biomass. Policies mandating a certain percentage of energy from renewable sources can create a stable demand for biomass energy.

Innovation Grants: Grants and funding for research into new applications of Miscanthus, such as bioplastics or biofuels, can open additional revenue streams. Support for pilot projects can help high-value product generators prove concepts and scale production.

Partnerships and Joint Ventures: Collaborations with BVCM companies and breeders can lead to innovations that reduce costs or enhance product value. Joint ventures can also leverage shared expertise and resources to expand market reach.

5.3 Outcome(s) of conversations with prospective end users.

During 2023 and 2024 an independent report was commissioned to assess the Economic impact of IBERS. Biomass crops was a thematic area that was investigated and over 30 external consultees were interviewed by SQW. Consultations highlighted a sense that momentum is starting to build around biomass crops although currently the identified economic impact remains potential rather than actual. They also highlighted that IBERS is seen as an important source of independent and credible expertise on biomass crops, and both strategic stakeholders (policymakers in government departments, funders, etc.) and commercial partners value the facilities, land resource and world class expertise. In addition, the Seed Biobank, the novel varieties developed through the breeding programme, and contributions made to new processes and products, were all identified as key enablers that could help unlock the economic potential of biomass crops going forward. The underlying R&D undertaken at IBERS was viewed by consultees as a vital platform that will unlock future economic impact, that in part will be generated by other economic agents. The team have significantly advanced the science and understanding of biomass crops, helping make the crops a more viable proposition for end users and farmers by addressing knowledge gaps that might otherwise slow or block adoption. The findings in relation to Miscanthus are summarised in Figure 17.

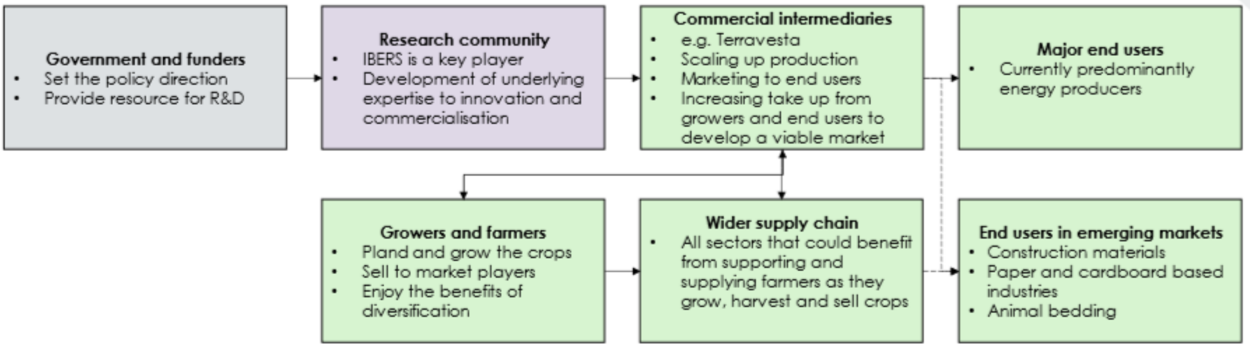

Figure 17 Route to impacts in the Biomass crops theme (from the SQW report)

In terms of Miscanthus production in the UK, and beyond, the major barrier to uptake is at the grower stage. This can be attributed to a number of factors:

- Lack of familiarity with the crop, or perennial cropping systems
- Lack of incentives to overcome the initial costs and delayed return on investment
- Lack of joined up infrastructure to ensure robust supply chain demand
- Land ownership: 30-40% of UK farms are tenanted, with the average tenancy lasting less than 4 years

We have met with key stakeholders including potential growers, farmers unions, end users, and policy makers in Wales and the UK (see section 7.1).

Based on interviews and a workshop with existing Miscanthus and short rotation coppice (SRC) willow growers and associated stakeholders, a recent publication outlines the barriers and enablers to biomass crop uptake in the UK (Ingram *et al.*, 2025). Motivations to grow Miscanthus included the opportunity to generate an income from unproductive land, and Miscanthus is seen as a low maintenance crop, with low time and labour demands, attractive for those approaching retirement. This is an important factor given the average age of farmers in the UK. Planting grants, fixed market price and alternative markets such as animal bedding were additional motivating factors. Many farmers observed a range of environmental benefits, including improved soil heath, a reduction in erosion under wet conditions, increased soil nutrient levels and increased biodiversity in terms of insects and birds, presumed to be from reduced pesticide use.

Miscanthus compares well with other crops economically, even accounting for higher establishment costs, and is financially attractive on unproductive land. Despite this, uptake has been lower than anticipated, indicating that there are other reasons deterring farmers. it was noted that growing Miscanthus requires a substantial change in thinking, but is compatible with environmental drivers, soil improvement, and farm diversification. Ultimately it is recognised that growing Miscanthus needs to be financially sustainable for farmers and that more evidence is required for them to be able to take the decision to plant the crop.

The majority of Miscanthus planted to date is on former arable land, with some interest from grassland areas such as in Wales where livestock numbers are reducing. Proximity to an end user is important to reduce transportation costs; in practice this is primarily power stations. Establishment was challenging for some growers, with difficulties replanting patches within the crop. However, there was consensus that the crop is easy to care for once established. Access to specialist equipment was difficult for some and it was hoped that costs would decrease as the technology matures. Support is required in terms of grant applications, advice, planting, accessing machinery, harvesting, and contracts.

When IBERS hosted the Young Farmers Next Generation group, of all our crops it was Miscanthus that generated the most interest, with extensive questions posed around environmental benefits as well as logistics. Familiarisation with the crop, its agronomy, and its benefits, is seen as a key factor in overcoming the stagnation in planting. We have developed a mobile display for use at events and in discussion with farmers (Figure 18).

5.4 Information provided by DESNZ acceleration support

The report prepared by Sustainable Ventures comprised a comprehensive strategy for the commercialisation and scale-up of Miscanthus varieties resulting from Miscanspeed innovation. The report focuses on addressing key challenges, leveraging opportunities, and defining actionable steps for AU and its stakeholders to establish Miscanthus as a cornerstone of sustainable agriculture and the bioeconomy. It serves as a roadmap for AU and its stakeholders to effectively translate research and development efforts into successful commercial outcomes, ensuring broader adoption and contributing to a sustainable global bioeconomy.

Figure 18 Chipped and baled Miscanthus on display at RWS Grassland and Muck event at Trawscoed, Aberystwyth

5.4.1 Key Findings from the analysis of the Miscanthus ecosystem, its market dynamics, potential revenue streams, and the strategic role of AU.

Miscanthus Ecosystem and Market Dynamics

- The current Miscanthus ecosystem is underdeveloped, with limited grower adoption, fragmented supply chains, and a predominant focus on bioenergy applications.
- AU plays a pivotal role in the research and development of improved Miscanthus varieties, particularly through its expertise in genomic selection and speed breeding.
- While bioenergy remains the primary market, emerging applications in biochemicals (e.g., xylitol), bioplastics, biochar, and construction materials offer significant opportunities for revenue diversification and market expansion.
- Miscanthus offers substantial environmental benefits, including carbon sequestration (2–3 tonnes per hectare annually), biodiversity enhancement, and soil health improvements.

Benchmarking with Comparative Crops - Benchmarking analysis with other successful biomass crops, such as willow, switchgrass, and sugarcane, reveals key strategies for the successful commercialisation of Miscanthus. These include:

- Prioritising market diversification to enhance profitability and market resilience.
- Securing strong policy support, including financial incentives and subsidies, to encourage grower adoption.
- Developing efficient seed-based propagation systems to reduce upfront costs and logistical barriers for growers.

Key Challenges - The Miscanthus industry faces several challenges that need to be addressed to achieve widespread adoption and commercial success. These include:

- High establishment costs (£1,500–£2,000 per hectare) and long payback periods, which deter grower adoption.
- Inefficient supply chains with high transportation costs and limited processing infrastructure.
- Policy uncertainty and a lack of long-term contracts, creating market instability.
- Limited genetic diversity in current Miscanthus varieties, increasing vulnerability to pests and diseases.

5.4.2 Key recommendations - focusing on strategies to mitigate challenges and unlock the full potential of Miscanthus.

5.4.2.1 Short-Term Recommendations (2025-2027)

These recommendations focus on reducing risk for growers and establishing a solid foundation for the Miscanthus market.

Leverage Breeding Innovations and Seed Production

- Aggressively leverage **genomic selection and speed-breeding technologies** to rapidly develop high-yielding and resilient Miscanthus varieties.
- Prioritise key traits that enhance **yield, resilience, and biomass quality**, such as high biomass output, stress tolerance, and optimal composition for different end uses.
- Transition to **seed-based hybrids** to achieve a cost-effective production model for growers.

Strategic Licensing and Partnerships

- Develop targeted partnerships with key players across the value chain, including energy companies, biorefineries, and agronomy service providers.
- Partner with **energy companies like Drax** for long-term biomass supply agreements and integrate Miscanthus into BECCS.
- Collaborate with **biorefineries** to explore high-value products like xylitol, bioplastics, and biofuels.

Diversifying Revenue Streams

- Develop a diverse portfolio of products and services beyond biomass for energy, including high-value chemicals, biochar, animal bedding, and construction materials.
- Partner with biorefineries to produce high-value chemicals like xylitol, furfural, and levulinic acid from Miscanthus.
- Integrate Miscanthus cultivation into carbon credit schemes and promote biochar production for soil improvement and carbon sequestration.

Strengthening Grower Engagement

- Provide **financial incentives and subsidies** to offset establishment costs and reduce financial burden on growers.
- Offer **agronomy support**, training, and best practice guidance to Miscanthus growers to ensure successful establishment and management.
- Launch a **digital advisory platform** with access to digital tools, weather-based recommendations and best-practice guidance.

Develop Consulting Services

- Offer customised **agronomy packages**, including site assessments, planting schedules and crop management plans.
- Expand **demonstration farms** to showcase high performing Miscanthus varieties and best practices.

Maximise Royalty Income

- Promote **seed-based propagation** systems, structuring royalties based on biomass yield or quality.
- Collaborate with **carbon trading platforms** to monetise Miscanthus's carbon sequestration potential.

Branding and Marketing

- Develop comprehensive marketing strategies to highlight the environmental benefits of Miscanthus, emphasising its carbon sequestration and contribution to renewable energy goals.

- Build strong relationships with growers and demonstrate a track record of success through case studies.

Pilot Programs

- Implement pilot programs for different business models to test their feasibility and gather data on profitability and scalability.

5.4.2.2 Long-Term Recommendations (2028–2035)

These recommendations focus on scaling production and adoption, enhancing supply chain efficiency, and diversifying revenue streams.

Scale Production and Adoption

- Prioritise the use of marginal or degraded land for Miscanthus cultivation to reduce competition with food crops and enhance biodiversity.

- Explore options for integrating Miscanthus into existing agricultural systems through rotational planting or intercropping.
- Focus on international expansion by licensing Miscanthus varieties and technologies to regions with high biomass demand and favourable policy environments, such as Europe and the USA.
- Develop partnerships with international stakeholders to facilitate market entry and regional adaptation of Miscanthus varieties.
- Invest in research and development to enhance the efficiency of Miscanthus biomass conversion technologies.
- Explore advanced biofuel production pathways, such as cellulosic ethanol and bio-jet fuel, to address the growing demand for sustainable transportation fuels.

Develop High-Value Applications

- Focus on biochemical production by partnering with biorefineries to explore high-value chemicals such as xylitol and nanocellulose.
- Expand biochar production, optimising the process and creating new products for soil improvement and carbon sequestration.
- Partner with manufacturers to develop Miscanthus-based construction materials such as insulation and biocomposites.

Enhance Supply Chain Efficiency

- Establish integrated value chains that connect growers, processors, and end-users, ensuring a steady supply of high-quality Miscanthus biomass and products.
- Explore innovative logistics solutions, such as mobile processing units and the densification of biomass for easier transportation.

"Blue Sky" Ideas

- Explore the potential for vertical farming to improve seed production.
- Develop integrated biorefineries for multiple products.
- Explore novel applications such as phytoremediation, biocomposites, decentralised biorefineries, 3D printing bioplastics, and floating plantations.

5.4.3 Key Next Steps

To translate the recommendations outlined in this report into tangible actions, it is essential to define specific next steps for both the short and long term. These next steps should focus on pilot projects, stakeholder engagement, market development, data-driven decision-making, and ensuring the financial sustainability of the Miscanthus breeding program.

Pilot Projects

- Launch regional demonstration projects to validate business models and optimise agronomic practices. These pilot programs should focus on key regions and

involve collaboration with growers, energy companies, and biorefineries to test different production and commercialisation models.
- Conduct pilot trials for high-value applications of Miscanthus, such as the production of biochemicals (e.g., xylitol) and biochar. These trials should focus on optimising production processes, evaluating the quality of the final products, and assessing the economic viability of these applications.

Stakeholder Engagement

- Organise workshops, conferences, and online forums to engage with growers, policymakers, and industry stakeholders. These events should focus on knowledge sharing, building relationships, and promoting the benefits and potential of Miscanthus.
- Build strong partnerships with energy companies and biorefineries to secure long-term contracts and market access for Miscanthus biomass and products. These partnerships should focus on creating a stable demand for Miscanthus and ensuring fair pricing for growers.

Market Development

- Develop and implement targeted marketing campaigns to increase awareness of Miscanthus among farmers, investors, and consumers. These campaigns should highlight the economic and environmental benefits of Miscanthus and its diverse applications.
- Establish regional knowledge hubs and demonstration farms to facilitate training and knowledge sharing on Miscanthus cultivation and utilisation. These hubs should provide growers with access to the latest research, best practices, and technical support.

In conclusion, Miscanthus represents a transformative opportunity for the bioeconomy, offering significant environmental, economic, and social benefits. By addressing current challenges, diversifying applications, and scaling production, AU can position itself as a global leader in Miscanthus innovation and commercialisation.

6. Secondary Project Benefits

6.1 Dissemination activities undertaken including media coverage

Knowledge exchange and dissemination activities were aimed at policy, stakeholder, public and academic engagement. Over the duration of the project, a total of **seven** activities have been produced/co-produced by the project specifically for the purpose of sharing/exchanging knowledge (KPI three to five) with **over twenty** events attended by members of the project to share/exchange knowledge about the project

(KPI six to ten). These activities have played a key role for the project engaging each group in discussions on the versatility and benefits of Miscanthus.

POLICY – We aim to provide an evidence base to policy-makers and others to inform the development of the Miscanthus biomass value chain from feedstock production, through processing, to end use.

Engagement with policy leaders and government officials have taken place through visits to the Institute as well as at external meetings and events. Examples include: Discussions with Members of UK Parliament and UK Government, the First Minister (Figure 19), Secretary and Under-Secretary of State for Wales, the Chief Scientific Advisor and Climate Change Minister for Wales. Attendance at Wales Innovation Network events in London and Brussels which brought together researchers from Wales and partners across Europe collaborating on key mutual challenges such as Net Zero. Miscanspeed staff attended the annual Royal Welsh Agricultural Society show, where round table discussions were held with policy leaders.

Figure 19 Meeting with First Minister Mark Drakeford in Brussels

Conversations have highlighted the benefits of Miscanthus and the need to incorporate biomass crops into policies incentivising sustainable land use. In response to demand for an up-to-date evidence base, IBERS led a peer–reviewed community publication 'Upscaling miscanthus production in the United Kingdom: The benefits, challenges, and trade-offs' (Hodgson *et al.*, 2024).

The IBERS Miscanthus team are actively engaged in policy development for UK and devolved administrations in relation to biomass crops and their role in net zero. IBERS has contributed to separate Welsh Government consultations on the Sustainable Farming Scheme (SFS) and the Skills needed to achieve net zero in the agriculture sector (December 2023). This has also led to providing evidence to the Welsh Government Climate Change, Environment & Infrastructure Committee on the SFS (March 2024), SFS: Carbon Sequestration Evidence Review Panel (August 2024), and a meeting with the Minister for Culture, Skills and Social Partnership and Minister for Further and Higher Education (Welsh Government) on Green Skills

(January 2025). In the last 12 months we have given evidence to the Climate Change Environment and Infrastructure Committee (Welsh Government, March 24); Responded to a Scottish Government consultation on biomass crops policy (June 24); Met with Ceredigion County Council to discuss their plans for a hydrogen economy (July 24); Given oral evidence to the Welsh Government's Carbon Sequestration Evidence Review panel (July 24); Hosted a visit from the Defra Soil Health team (Sep 24); Participated in a Climate Change Committee roundtable on principles for Land Use Change (Oct 24); Discussed with the Climate Change Committee the outcomes of a Wales Net Zero 2035 project we were involved in (Dec 24); Been ongoing active members in the Welsh Government's Agriculture Industry Climate Change Forum; Contributed to policy engagement via the 'Land Use for Net Zero, nature and people' (LUNZ) Hub.

STAKEHOLDERS - We aim to understand and connect components of the Miscanthus supply chain. A key target is to familiarise potential growers with the crop.

Figure 20 IBERS/Miscanspeed stand at the Low Carbon Agricultural Show 2024

Engagement with stakeholders included reciprocal visits to industry leaders such as Drax where discussions focused on biomass policy and the requirements of upscaling biomass, providing information for them as an end user of the product, discussions with the President and policy team from the Farmers Union of Wales on industry challenges. Attendance at the Low Carbon Agricultural Show, an event well attended by farmers and industry, which showcases low carbon practices, technology and energy solutions for a profitable and sustainable farming future (Figure 20); the annual Royal Welsh Agricultural Society show and additional Royal Welsh Show events including the annual Winter Fair, and the Grassland and Muck event that we hosted at Trawscoed farm, AU, in 2024 (Figure 21). We have showcased Miscanthus bedding to farmers and successfully trialled Miscanthus bedding for the AU alpacas, who are apparently particular about their bedding material (Figure 22).

Interested parties were able to learn about the crop and its many uses, and how they might benefit from producing or using Miscanthus.

IBERS was featured on Ffermio, S4C's countryside and farming magazine series. Presenter Alun Elidyr attracted attention at the IBERS stand at the Royal Welsh Winter Fair, drawing in farmers interested in Miscanthus where we were able to showcase Miscanthus bales and highlight the planting grant currently available to Welsh farmers.

PUBLIC – Our aim is to engage the public in dialogue about renewable energy and sustainable agriculture solutions, and the role that Miscanthus can play.

Figure 21 Visitors viewing the Miscanthus plots at the Grassland and Muck event at Trawscoed, Aberystwyth in May 2024

We attended events such as the annual Royal Welsh Agricultural Society's show and engaged with local schools during British Science Week. A collaboration with local printmakers (Appendix 4) culminated in an exhibition of artworks printed onto paper.

ACADEMIC – Our aim is to showcase our work and collaborate with world-leading researchers.

Attendance at the annual Plant and Animal Genome Conference in San Diego where presentations were given on the project and on Sparse Testing designs. This conference is the largest ag-genomics meeting in the world where Miscanthus research is presented to the international community. Presentations were delivered at the Association of Applied Biologists (AAB) conference which provides a forum to meet and discuss the state of the art in biomass and energy crops and attendees visited the Biomass Connect plots at Aberystwyth (Figure 23).

Figure 22 Aberystwyth University alpacas demonstrating the beneficial properties of Miscanthus bedding at the Grassland and Muck event at Trawscoed, 2024

Figure 23 AAB Biomass and Bioenergy Crops VI

6.2 IP generated from project.

- Molecular markers, GS models and predictions
- Speed breeding 'recipes' and understanding of Miscanthus phenology

We are in discussion with our innovation advisors in relation to protection of IP and its potential for wider use.

6.3 Number of jobs created and improving skills/experience in sector.

A total of six jobs were created to deliver the project, four posts were science/business professionals with two technical professionals.

Skills development:

Project leadership and management: The project has been managed by a project lead with the support of two project managers. Skills have been developed in the areas of governance, risk management, finance, recruitment, and science to understand, monitor and report on the progress of the deliverables applied to the project.

Technical: The project has been delivered by science professionals who have led on the work packages related to field trials, genomic selection and speed breeding. The work package leads have been supported by two post-doctoral research associates and three technicians over the duration of the project. Skills have been developed in the areas of genomic marker development, breeding, field trials, genomic selection, speed breeding and CE customisation. The project was able to draw on support from established internal personnel to help during delays to recruitment, absence for sickness and annual leave, and busy/critical periods.

Stakeholder engagement: All Miscanspeed staff have contributed to and attended various stakeholder engagement activities spanning open days, events, meetings, media appearances etc. Much of our stakeholder engagement is conducted through the medium of Welsh, as many of our primary stakeholders have Welsh as their first language.

Engagement with other Lot 1 projects has been an important component of widening our understanding of the UK biomass landscape. The project also benefitted from the guidance of its external advisory board members.

The potential for Miscanthus In terms of the sector more broadly, in a commissioned report on 'The socio-economic and environmental benefits of UK Miscanthus production' ADAS calculated that the 8,000 ha of Miscanthus currently grown supports approximately **137 FTE** jobs in the UK, spanning production of plant material, ground preparation, crop establishment and management, crop marketing and sales, technical and transportation and logistics. Assuming an increase of 24,000 ha/year, with approximately 600,000 ha planted by 2050, they project approximately **8,300 FTE** positions created by Miscanthus production.

6.4 New partnerships formed from project (UK and International).

Three new contractual partnerships have been formed as a result of the project, three based in the UK and one in the US.

Three research sub-contracts were awarded: the first being at the outset of the project with Energene Seeds Ltd. who set up and managed the trials at the southern latitude crossing site based in the Canary Islands. This company has extensive knowledge and experience of growing Miscanthus as well as technical, environmental and commercial knowledge. They also produced a commercialisation report for the project.

Tenders were prepared for the appointment of companies to process and sequence the DNA samples and to generate genomic markers for analysis (awarded to a company based in the US) and the production of a report on the socio-economic and environmental benefits of UK Miscanthus production (awarded to a company based in the UK).

Partnerships were also established with a local design company who worked with the project on the development of literature and promotional materials for events and dissemination activities and a local blacksmith company to produce bespoke materials to introduce an innovative method of root containment to prevent the mixing and contamination of the elite lines to maximise opportunities for the production of varieties being developed for commercialisation.

Miscanspeed staff have worked with Lot 1 projects Accelerating Willow Breeding and Deployment, OMENZ and TaedaTech as well as Lot 2 project Biomass Connect. In TaedaTech we provided Miscanthus which was successfully trialled for propagation in their aeroponic system.

The Miscanspeed project has further established us internationally as leading experts in Miscanthus research and breeding, which will lead to future collaborations, international partnerships and revenue generation.

7. Project Management

7.1 Brief description of structuring and scheduling of project

The governance structure for the project consisted of an External Advisory Board (Prof. Gancho Slavov, Prof. Richard Flavell, Peter Coleman, Jess Winnan and the much missed Prof. Ian Macay), who provided strategic oversight to the project management board. This included experts in theoretical/applied GS in plant breeding, along with industry and policy representatives. The project management board consisted of the Principal Investigator (project lead), work package leaders and project managers.

Monthly meetings were held with a Monitoring Officer (appointed by DESNZ) and attended by a Project Manager from DESNZ. Quarterly reports were submitted, financial claims submitted every six months followed by a stage gate review and an annual site visit.

7.2 Brief description of key risks and mitigations, and detail of any risks that materialised into issues.

A risk register was created with risks grouped into the following categories: Governance and Staffing, Technological, Environmental, Financial.

The risk management process followed key steps to manage and minimise any potential negative impacts to the project:

- Risk identification: recognising potential risks that could impact the project

- Risk evaluation: assessing the probability and impact of the identified risks and prioritise (low, medium, or high)
- Risk monitoring: keeping a track of identified risks with register updates submitted on a quarterly basis.
- Risk mitigation: development of strategies/actions to reduce or eliminate the risk

7.3 Project management lessons learned.

- **Clear Project Scope and Requirements**: Clearly defined project goals, deliverables, and scope from the start ensured that all parties agreed on these aspects to avoid frequent changes during the project lifecycle.
- **Effective Communication**: Open lines of communication at all levels is key for the project e.g. regular project/technical meetings, monitoring officer meetings, site visits & with other projects within the NZIP.
- **Risk & Change Management**: Continuous monitoring of risks throughout the project was essential to identify and develop effective mitigation measures and ensured successful delivery of the project. Additionally, any changes to the scope/budget/project were planned, documented and assessed through a robust change control procedure with DESNZ.
- **Stakeholder Engagement**: Advanced planning and preparation are essential, as is coordination with organisers and other attendees, if maximum benefit is to be achieved.

8. Conclusions and next steps

8.1 Was the project able to achieve its objectives?

Miscanspeed has been extremely successful in delivering both its original ambitious objectives and also additional innovations, summarised below.

Objective 1. Implement Genomic selection in Miscanthus species Msin and Msac recurrent selection populations.

Develop cost effective genomic markers for Msin and Msac training sets: Following a tendering process, Rapid Genomics (now LGC Genomics Ltd.) were selected to undertake marker development for our Miscanthus training sets. Initial marker discovery was based on DNA from our two recurrent selection populations. We then added existing markers from an additional training set of ~1000 diverse Miscanthus genotypes to ensure the resulting marker set had wide applicability to all known Miscanthus to avoid marker incompatibility issues in the future. A 50K marker panel was then developed from the full marker set, following a cost benefit analysis of reducing marker numbers.

Phenotype Msin and Msac training sets, in both Germany and the UK: The Msin and Msac recurrent selection populations were phenotyped in a breeder's field in Germany at the start of the project. Biomass yield and other traits were measured at peak yield in autumn, and at harvest the following spring. The rhizomes were then dug from the field and planted as a replicated field trial in Aberystwyth in order to validate the GS models at the end of the project.

Develop and implement GS models for the Msin and Msac recurrent selection populations: Phenotypic and genotypic data was combined from the Msin and Msac training populations to generate GS models for the two populations. Following recreation of C0 from the training set parents, the progeny were genotyped and ranked using the Msin and Msac GS models. The top 20 progeny were selected as parents for crossing to generate the subsequent generation (Figure 24).

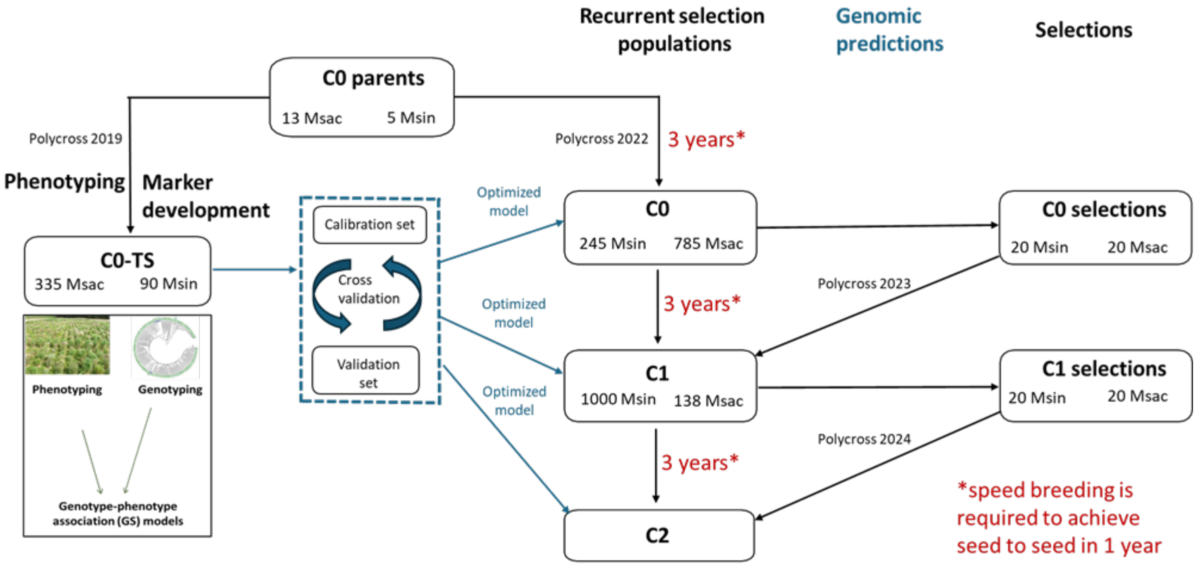

Figure 24 Summary of the Miscanspeed project, including plant numbers for each population and generation

Southern Latitude crossing site (Energene Seeds Ltd.): The parents of the Msin and Msac training set populations were sent to our Southern crossing location run by Energene Seeds Ltd. and planted in crossing blocks. Flowering time data for each plant and meteorological data were collected. Seed were harvested and brought to Aberystwyth for marker analysis and GS. Selected progeny were returned to the southern crossing site for subsequent rounds of crossing and seed set.

Extend GS to include GxE – Sparse Testing: Following rounds of selection within a breeding program, it is essential to evaluate the selections of interest in multilocation trials to ensure they perform across a range of environments. This stage is time consuming and costly, typically involving one or more years of clonal propagation of plant materials to establish the trails prior to a minimum of three years for the crop to reach maturity in the UK and multiple years phenotypic evaluation across the multilocation trial sites.

Sparse testing is a form of GS in which the phenotypic information of lines/genotypes is split across environments. Including G×E interaction in GS models (Sparse Testing) improves the accuracy of predicting genotypes and reduces the cost of multilocation trailing by evaluating a subset of the progeny in each location. For example, in our recent analysis, 20% of the population was selected as the training set while the remaining 80% were the testing set in each of the testing environments. The training set was used for predicting the unobserved genotypes (the testing set) in each environment. We observed that maintaining 20% of the phenotypic records in the multi-environment training set achieved a moderate predictive ability. This suggests that the cost of phenotyping genotypes in multilocation trials could be reduced by up to 80% since only 20% are phenotyped, hence saving cost. Similarly, the testing capacity could be increased by fivefold for a fixed budget. Furthermore, the clonal propagation step is avoided, saving additional years and associated costs.

The accuracy of predicting unobserved genotypes in multilocation trials is influenced by the number of genotypes across environments, the number of environments where each genotype is tested, the prediction model, and the number of phenotypes per genotype (Jarquin *et al.*, 2020). Different cross-validation strategies have been conducted to simulate different problems that breeders face at different stages of the breeding pipeline and assess the impact of incorporating G x E on GS predictive ability. Proof of concept for Sparse Testing has been established in Miscanthus and should be incorporated into future breeding pipelines.

Outcomes:

- A robust, cost-effective, marker set relevant for all Miscanthus genotypes has been developed and is available to the community.
- A comparison of trait rank orders between two geographic locations, and validation of the GS models used.
- Rank orders for all progeny were produced for two generations of Msin and Msac, with the 3rd expected within the three years of Miscanspeed. This enabled 3 rounds of selection in the time usually required for one generation.
- Annual seed set was achieved to enable subsequent generations of GS, and associated phenology and meteorological data captured to inform the speed breeding.
- Beyond the original scope of the Miscanspeed project, Sparse Testing is an additional innovation which will save both time and money in the final multilocational trialling stage of the Miscanthus breeding program.

Objective 2. Develop speed breeding in Miscanthus species Msin and Msac to achieve seed to seed within a year in the UK.

Establish bespoke glasshouses for Msin and Msac: Glasshouses at IBERS were modified to target: Intercanopy lighting; Improved control of vapour pressure deficit, Lowering thermal time while increasing biomass accumulation (Msin); increasing biomass accumulation (Msac) and Optimising nutrient availability through irrigation frequency.

Optimise flowering and fertile seed set in Msin and Msac: Msin and Msac plants were grown under simulated El Heiro conditions in the customised CE. Flowering of individual stems was monitored in relation to stem growth. Where flowering occurred, recurrent populations were open pollinated. Seeds were harvested and sown onto sand to test germination rates.

Compare environmental conditions and phenology between the Southern crossing location and the bespoke glasshouses: Environmental data was produced from both CE and the southern crossing site to enable comparison. Degree days and average temperatures tracked the southern crossing site well. Lower Msin seed set in the field was attributed to strong winds and additional wind protection was provided to mitigate for this.

Outcomes:

- Bespoke facilities to regulate and analyse Miscanthus phenology
- Flowering time in both Msin and Msac was synchronous between the customised CE and the southern crossing site once additional far-red LED lighting was introduced for Msac.
- In year 2, greater Msin seed set was achieved in the CE than the southern crossing site, and germination rates were also better.
- Additional Msin selections were grown in the same compartment as the Msac selections and both species flowered synchronously.
- Optimised light recipes to maximise seedling establishment, plant growth, flowering and seed set may be an additional opportunity for innovation.

8.2 Lessons learned (technical, project management, interaction with supply chain, general and regulatory barriers or hurdles).

Technical: In Y1 of the Miscanspeed project, a new team was formed with a focus on technical expertise across a range of disciplines.

Risk mitigation strategies included working with both Msin and Msac to avoid reliance on a single population, leading to key insights into the species' challenges and flowering synchronization for hybrid breeding. Best practices for Miscanthus plant husbandry were implemented, alongside the development of new protocols for quality assurance, such as improved plant labelling and optimized seed establishment and leaf sampling.

The feasibility of applying GS to Msin and Msac was confirmed, with the creation of a cost-effective marker set, and future efforts will focus on phenotyping, GxE studies, and hybrid development. Additionally, CE techniques were developed for speed breeding Msin and Msac in the UK, refining phenology regulation for each species.

Project Management: The project was successful due to a clear scope and well-defined requirements, ensuring all parties were aligned on goals and deliverables from the start to avoid unnecessary changes.

Effective communication through regular meetings, site visits, and collaboration with other projects within NZIP was crucial, while risk and change management processes helped mitigate issues, ensuring the project stayed on track.

Stakeholder engagement was strengthened through advanced planning and coordination with organizers to maximize the benefits of involvement.

General/regulatory barriers or hurdles: There are currently no regulatory barriers or hurdles impacting the project.

The lack of an integrated strategy to incentivize biomass growers, particularly in relation to other schemes, highlights a need for better coordination and alignment to drive growth in this sector.

9. End matter

9.1 References

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9.2 Appendices

Appendix 1. CPVO registration search (03/12/24) – Mxg types

Table A2 CPVO registration search (03/12/24) – Mxg types

Denomination	Species	Grant number	Status	Applicant(s)	Application date	Application number	Title status
Aphrodite	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	63259	Granted	Aberystwyth University; Ceres Inc.	27/11/2020	20203045	Approved
Artemis	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	63257	Granted	Aberystwyth University; Ceres Inc.	27/11/2020	20203043	Approved
Astraea	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	61076	Granted	Aberystwyth University; Ceres Inc.	24/12/2018	20183177	Approved
Atropos	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	61073	Granted	Aberystwyth University; Ceres Inc.	24/12/2018	20183176	Approved
Bia	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	61030	Granted	Aberystwyth University; Ceres Inc.	29/11/2019	20193246	Approved
Boreas	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	63258	Granted	Aberystwyth University; Ceres Inc.	27/11/2020	20203044	Approved
Brontes	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)	63260	Granted	Aberystwyth University; Ceres Inc.	27/11/2020	20203046	Approved

Appendix 2. Relevant UK legislation

Contracts for Difference: https://www.gov.uk/government/publications/contracts-for-difference/ contract-for-difference

The Green Gas Support Scheme Regulations 2021 [Online]. Available at: https://www.legislation.gov.uk/uksi/2021/1335/contents

The Greenhouse Gas Emissions Trading Scheme Order 2020 [Online]. Available at: https://www.legislation.gov.uk/uksi/2020/1265/contents

The Renewable Heat Incentive Scheme Regulations 2018 [Online]. Available at: https://www.legislation.gov.uk/uksi/2018/611/contents

The Renewable Transport Fuel Obligations Order 2007 [Online]. Available at: https://www.legislation.gov.uk/uksi/2007/3072/contents

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Appendix 3. IBERS Miscanthus background IP and funding up to 2021

Table A1 Domestication of the bioenergy crop Miscanthus (UK Plant Science Strategy)

Box 3.3: Domestication of the Bioenergy Crop Miscanthus[53] – In Commercial Field Trials.

Technology Readiness Level	Dates	Funder	Indicative Investment	Output
3-4	2005	Defra	£10K	Evaluation of germplasm collected from UK and EU projects including wild accessions, breeder's lines & commercial hybrids.
1-3	2006-11	Defra, BBSRC, Ceres Inc.	£500K	Collection of wild germplasm in China, Japan, South Korea & Taiwan, with quarantine in UK, to extend genetic diversity with relevant agreements providing commercial freedom to operate.
3-5	2012-	BBSRC	£100K	Implementation of UN protocols on the Convention on Biological Diversity with Access & Benefit sharing agreements.
1-3	2008-	BBSRC, EPSRC, EU	£5M	Phenotypic characterization of key traits in wild germplasm and novel progeny.
2-4	2012-	BBSRC, Defra, Ceres Inc., Innovate-UK, Terravesta Ltd.	£10M	Development of methodology to perform wide interspecies crosses to generate heterosis. Development of seed-based (as opposed to rhizome-based) propagation to enable upscaling.
1-4	2014-	BBSRC	£500K	Development of genomic prediction techniques to accelerate rates of genetic improvement.
1-3	2010-	NERC, Energy Technologies Institute, EPSRC, BBSRC	£500K	Assessment of environmental impacts (GHG emissions, soil carbon and hydrology) of land use change involving Miscanthus.
4-7	2017-	Ceres Inc., Terravesta Ltd, EU H2020	£5M	Novel seed based and clonal varieties trialled in UK and Europe, in plots, field and commercial scale. Selected varieties[54] under registration trials from 2019, and licenced to Terravesta Ltd.

Potential impact: Assuming 50% of the 700,000 ha Climate Change Committee target for perennial biomass crops in the UK[12] was planted with Miscanthus, there would be 1 MtCO2e emissions savings in the land sector and an extra 5.5 MtCO2e from the harvested biomass (e.g. when used with carbon capture and storage).

Appendix 4. Miscanthus paper art exhibition

Figure A1 The collaboration between Aberystwyth Printmakers and Miscanthus researchers (A) culminated in an exhibition including information on Miscanthus and the papermaking process (B) and artworks printed onto paper made from Miscanthus grown at Aberystwyth (C).

Appendix 5. Miscanthus companies in the UK and beyond

Table A3 Miscanthus companies in the UK and beyond

Company Name & Website	Country	Description
Terravesta Ltd terravesta.com	United Kingdom	A leading Miscanthus biomass specialist, providing sustainable energy solutions through Miscanthus giganteus planting and supply chain management.
Miscanthus Nursery Ltd (MNL) carbontrap.org	United Kingdom	A cooperative with over 16 years of experience in providing planting, harvesting, and long-term biomass supply solutions for sustainable farming.
MFiber mfiber.co.uk	United Kingdom	Specializes in producing Miscanthus-based products for various applications, including animal bedding and biofuels.
Miscanthus d.o.o. miscanthus.eu	Croatia	Implements turn-key solutions for establishing Miscanthus plantations and consults on the development of Miscanthus feedstock supply chains across Europe.
Novabiom novabiom.com/en/	France	Dedicated to the development of Miscanthus cultivation and valorization in France and Europe since 2006.
Biomass Power Plant Fürstenwalde N/A	Germany	A biomass power plant in East Germany, operated by BKC B.V., sustainably heating 400 houses using Miscanthus and green waste.
BKC B.V. bkcbv.nl/	Netherlands	Utilizes Miscanthus for biofuel and as absorbent, odorless stable litter. Operates a biomass power plant in Germany using Miscanthus for sustainable heating.
MiscanthusGroep miscanthusgroep.nl/	Netherlands	A Dutch farmers' group focused on improving the growth and production of Miscanthus for sustainable agriculture and bio-economy.
Terravesta Europe terravesta.com	Poland	Established to meet the growing demand for sustainable perennial biomass in Europe, focusing on developing new markets.
New Energy Farms (NEF) newenergyfarms.com	Canada (operations in Europe)	Provides innovative planting systems and technologies for scaling up Miscanthus cultivation, with a focus on reducing establishment costs and time.