Title	Miscanspeed – accelerating Miscanthus breeding using genomic selection
Client	Department for Business, Energy & Industrial Strategy
Client reference	ABE-233-1-B
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Date	28th February 2022

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Contents

1 Miscanspeed Phase 1 Summary

Technology Feasibility: During Phase 1 of Miscanspeed we analysed our commercial breeding program and established the optimal Genomic Selection (GS) approach required to accelerate the development of new improved Miscanthus varieties for the UK market and beyond. We successfully tested some of the key limitations via statistical modelling, considered logistics, and demonstrated that GS has a high likelihood of success for key traits in our breeding populations. We generated a detailed plan of the phase 2 project, including the protocols required and the implementation of speed breeding, designed the bespoke modifications required to our facilities, and determined the most appropriate recurrent selection populations and traits with which to undertake GS. We determined the logistics for post-Brexit movement of seed and plant material, incorporating IBERS' unique UK point of entry quarantine status.

Market analysis: We surveyed UK Miscanthus supply, investigated demand, and identified critical failure points in the system to be addressed. We investigated 3 scenarios outlining the impact that implementation of GS could have on the capacity for UK biomass to reach its 2035 and 2050 targets. The potential scale of markets in other countries means that new Miscanthus varieties are a significant export opportunity.

Biomass supply benefits: We reviewed our approach to intellectual property and commercialisation, and the scope for future breeding being funded by royalty income. We analysed the bottlenecks for rapid upscaling of biomass supply and considered the opportunities for complementarity with other Lot 1 and 2 projects.

Accelerated genomic breeding is the only technology to offer a step change in the speed of delivery of new Miscanthus varieties to increase yield and overcome the limitations of the current clone Miscanthus x giganteus (Mxg), including resilience to environmental stresses such as cold and drought, and biological risks from pests and pathogens. Advances in complementary technologies in Miscanthus agronomy and harvesting, and similar innovations in willow, are also important to the UK's net zero ambition.

2 Context: UK and International policy context for perennial biomass crops and the role of Miscanthus

2.1 Demand for biomass crops to deliver decarbonisation

Increased availability of biomass is required for the decarbonisation of a wide range of sectors in the UK economy, including energy, transport, chemicals, manufacturing and construction, as outlined by the Climate Change Committee (UKCCC, 2018), which also emphasised the changing role of biomass between now and 2050. The UK Climate Change Committee's sixth carbon budget (UKCCC, 2020) indicates that in the long term, biomass should be used to sequester carbon, where this also displaces other emissions (i.e. Biomass Energy, Carbon Capture and Storage, BECCS). Future biomass demand is therefore highly dependent on successful implementation of UK Government greenhouse gas removal (GGR) policy. The UKCCC regards BECCS (including for power, industry, hydrogen, biofuels and bio-methane) as the predominant engineered GHG removal to be deployed by 2050 (52 out of a total of 57 $MtCO_2e$/year of engineered GHG removals in 2050 is assumed to come from BECCS in the balanced scenario).

The extent to which this is provided by UK biomass as opposed to imported biomass is similarly dependent on policy, but **under the UKCCC 'balanced net zero pathway', 700,000 ha of perennial biomass crops (assumed to be willow and Miscanthus) are indicated by 2050 (a total of 3% of UK**

land area), planted at a rate of at least 30,000 ha per year by 2035 (UKCCC, 2020). Other scenarios indicate up to 1.4 million ha. This compares to a current total planted area of approximately 8,000 ha Miscanthus and 2,000 ha of willow (Defra, 2021), highlighting the urgency for rapid upscaling of biomass crops. Furthermore, biomass crops offer additional benefits to the local environment including soil carbon sequestration, improved biodiversity and flood management, which increase the attractiveness of UK production compared to imported biomass.

International context: Estimates vary according to underpinning assumptions, but potential areas available for perennial biomass crops in the EU have been stated as being 15 Mha (Forsell *et al.*, 2016), 7-16 Mha (Ruiz *et al.*, 2015) and 47 Mha (Deppermann *et al.*, 2016). More widely, estimates of international biomass available to the UK, as published in the UK and Global Bioenergy Resource Model (BEIS, 2017), dropped significantly between the 2011 and 2017 versions of the model, largely due to a decrease in the estimated land available (between 79% and 90% lower, depending on assumptions made regarding suitability of land for food production, which should be prioritised). **As indicated in the UKCCCs 'Biomass in a low Carbon Economy' (2018), at a global level, demand is likely to be substantially greater than supply under almost all scenarios. The lack of availability of UK produced biomass represents a significant missed opportunity and our reliance on imports will become increasingly unsustainable and costly as demand increases in other countries with ambitions to reach net zero emissions.**

Relative contribution of different biomass crops: Given the scale of ambition for perennial biomass crop planting in the UK compared to the current areas, we regard other biomass crops (e.g. willow, short rotation forestry) as being largely complementary to Miscanthus (Bauen *et al*. 2010). Whilst its peak yield is dependent on soil water availability, Miscanthus has a very high water use efficiency. Willow has a significantly higher water requirement and is therefore more suited to the Western UK. Proximity to potential end users of the biomass, grower preference and end market requirements (e.g. moisture content, processing requirements) are likely to impact as much as environmental factors on the choices made at a local level.

2.2 The role of Miscanthus in the biomass supply chain

Miscanthus is a perennial grass native to vast areas of Southeast Asia and into Russia. It uniquely combines the efficient C4 photosynthesis of maize and sugarcane with low temperature tolerance, making it a unique biomass crop for temperate zones.

Miscanthus is a carbon negative technology – the crop takes carbon dioxide (CO_2) from the atmosphere to grow and partitions the resulting photosynthate both above and below ground. While the above ground canes are harvested annually, using established technology used for forage maize, the extensive root system remains in the soil, as sequestered carbon. The annual harvest provides a reliable income stream for farmers and predictable input to the supply chain. Harvested biomass can be; a) used directly, e.g. as animal bedding, traditional or state of the art building materials, or moulded e.g. into food trays, car parts etc.; b) burnt to generate heat and power, releasing only CO_2 taken up during the growth of the plant, or combined with carbon capture and storage (CCS) to maximise carbon reductions. Alternatively; c) via biorefining technologies, the sugars from the biomass can be extracted and fermented to bulk fuels such as ethanol, or to high value chemicals, such as xylitol, and the remaining lignocellulosic biomass be burnt for heat and power. Using Miscanthus biomass directly sequesters the embodied CO_2 and when used for fuel the biomass displaces the use of fossil fuels. **Current commercial yields are approximately 12t/ha for at least 10 years in the UK. In Aberystwyth we are breeding to increase yield and to overcome current limitations of the commercial clone Mxg such as susceptibility to drought and frost that**

limit the productive geographical range. Future targets will include biomass composition to realise the full potential of Miscanthus to generate high value products that are currently fossil-derived.

Despite the urgent need for perennial energy crops (UKCCC, 2020), uptake has been relatively slow among farmers unfamiliar with the practicalities and business model associated with this novel crop. There are therefore a number of obstacles to be overcome if we are to realise the potential of Miscanthus to contribute to decarbonising the UK as well as the additional benefits of the crop. The vast majority of Miscanthus grown commercially worldwide has been Mxg, a naturally occurring inter-specific hybrid (*M. sinensis* x *M. sacchariflorus*), a sterile triploid clone that is clonally propagated from rhizomes. Numerous technical developments are aimed at decreasing the costs and increasing the efficiency of planting, establishment, harvesting etc.

Across Europe, there are a number of suppliers, and the triploid clone is marketed under various different names, although they all appear to be the same genotype (Glowacka 2015). A limited number of alternative clones are now available, including *Athena* (Terravesta) which is reported to have a higher yield than Mxg, as well as a higher calorific value and lower ash content when burnt. **While Mxg and *Athena* have many excellent traits, we are now aiming to generate novel varieties that not only outperform these and extend the areas over which Miscanthus might be commercially grown, but also to introduce genetic diversity into the crop. There is now an urgent need to develop new varieties for commercialisation, including seed-based varieties which offer the potential for population-based plantings and upscaling of planted areas at rates that cannot be achieved by rhizomes.**

3 The importance of breeding Miscanthus compared to other potential innovations in biomass feedstock supply chains

3.1 Benefits of plant breeding and genomic breeding

The ceiling for biomass supply is ultimately limited by the yield of the crop and the number of hectares on which it is grown. Producing new Miscanthus varieties targets both; improvements to yield and resilience traits will result in higher and stable interannual yields over a wider range of climate and land types.

The aim of plant breeding is to select plants with desirable characteristics and combine their genetic diversity whilst eliminating unfavourable traits. The characteristics required vary between crops, but typically include increased yield, quality traits, and environmental performance (e.g. resilience to climatic extremes, and to pests/diseases). Breeding programmes are continuous pipelines, with improved varieties emerging on a regular basis to meet the demands of the increasing human population, changing environment and altered functional emphasis, e.g. CCS as well as diverse end uses. The success of plant breeding is measured as genetic gain. This is the increase in performance that is achieved via breeding and is formalised in the Breeder's Equation ($R=h^2S$). The response (R) to selection is determined by the heritability (h) of a trait, and the difference in the mean of the value of that trait in the selection compared to the mean value of that trait in the population (S, the selection differential). **A recent review of the socio-economic and environmental impacts of plant breeding in Europe (Noleppa, 2016), has estimated that for the major arable crops, plant breeding has contributed 67% of the innovation-induced yield growth, with agronomy contributing the remaining 33%, highlighting the importance of accelerated breeding in addressing the urgent biomass supply challenge.**

Plant breeding cycles are long and require sustained effort in order to realise ongoing genetic gain over time. Breeding perennials has the additional challenge of a delay of a number of years per cycle while the crop matures. With the advent and development of next generation sequencing technologies, the cost of DNA sequencing has fallen, resulting in genome sequences being generated for numerous crop species. With the availability of high-throughput genotyping-by-sequencing type technologies, genomic breeding becomes possible, and breeding cycles can rapidly use the information encoded by the genome as markers to predict mature traits, thereby reducing timeframes and plant-handling costs relative to traditional breeding cycles. GS has emerged as the leading genomic breeding technique over recent years and is already applied in wheat, rice and maize. **With the publication of the Miscanthus genome (Mitros *et al.* 2020) and reduction in marker costs, now is the perfect time to apply GS technology in order to overcome the challenge of bringing new varieties to market in order to realise the potential of this multifunctional carbon negative crop.**

GS is a technology proven in other crops, with the potential to radically disrupt Miscanthus breeding. Whilst technical innovations in agronomy can reduce the performance gap (i.e. the difference between yield on farm and the theoretical maximum yield), the development of new varieties has the scope to result in a step-change in biomass supply, and as such, innovations that accelerate breeding are urgently needed in order for the UK Government to deliver on its net-zero commitments. This innovation is stand alone; it would not be negatively impacted by a lack of innovation elsewhere in the Miscanthus feedstock supply chain. Neither does it conflict with other innovations. However, there is clearly scope for cumulative benefits from innovations proposed in BEIS phase 1 projects; for example, innovations in establishment agronomy would allow the benefits of a higher yielding variety to be realised earlier in the plant life cycle (e.g. project OMENZ, Terravesta), and innovations in automated weeding and harvesting operations (e.g. as proposed by University of Glasgow) would increase profit margins and potentially expand the areas of land suited to Miscanthus. As stated in section 2.1, the UK ambition for scaling up domestic biomass production is extremely ambitious, and we therefore regard other crops (e.g. willow, short rotation forestry) as being entirely complementary to our intention to provide Miscanthus varieties to the UK market.

3.2 The need for new Miscanthus varieties

The commercial clone Mxg is a sterile triploid hybrid, propagated by rhizome. All clonally propagated material has ultimately arisen from a single wild plant, and is genetically identical (Dong et al, 2019). A monoculture has the potential to become susceptible to a pest or pathogen, e.g. small mammals, insects, fungi, bacteria or viruses, and without genetic diversity, if one plant is susceptible then the entire crop is at risk. The genus Miscanthus originates from a vast geographic area across South East Asia, and includes vast diversity both within and between the different Miscanthus species. In the wild Miscanthus is robust with relatively few pests and diseases, however as well as the natural toughness of the plant, this is likely due to the huge diversity within this outbreeding species in which every seed is a unique genetic combination. Asian pathogens of Miscanthus are primarily insects such as the stem borer which is not native here and would be identified and eliminated upon quarantine into the UK, however rusts have been observed on Miscanthus, highlighting the importance of maintaining mixed genetic populations, or planting mixes of different genotypes as is the practice in willow, to maintain diversity and hence resilience to whatever may harm the crop. Miscanthus is a perennial crop and so must survive and generate high yields over successive seasons; establishment costs are relatively high and return on investment is delayed as the crop takes a minimum of one growing season to establish before a commercial harvest can be taken. It is particularly important in perennials that plants remain healthy so as not to reduce the overall life span of the commercial crop.

Aberystwyth curates a large and diverse Miscanthus collection collected from across Asia. Its wide geographical distribution is associated with great diversity within the genus, including multiple species with different adaptations which provide an excellent resource for a breeding program, but also a challenge in terms of identifying the best material to select and combine. As well as the parental species, which may be diploid or tetraploid, intra- and interspecific hybrids occur naturally in the wild and wide hybrids can be generated even beyond the genus, demonstrating the plasticity and potential of the C4 grasses. The primary aim of the breeding program is to use this material to generate superior Miscanthus varieties in terms of crop yield, resilience and quality. Key to this is understanding the genetic potential of the different Miscanthus genotypes themselves, and how these can be combined to produce the optimal progeny and hybrids. There are multiple potential approaches in a breeding program, e.g. seed populations, selecting and combining clones from seed-based populations, or breeding F1 hybrids, each with advantages and disadvantages. **The GS approach we are proposing will further our understanding of the genomic underpinnings of the traits of interest and their heritability and robustness in recurrent selection populations. Application of this understanding will accelerate breeding of novel clones and seed populations. Outcomes will include optimised *M. sinensis* and *M. sacchariflorus* populations for use directly as mixed clones or populations, and also improved parents for future interspecific hybridisation.**

Extensive multi-location trials and modelling have revealed that the climatic and geographic limits to Mxg cultivation are primarily based on temperatures and water availability. By increasing the genetic diversity, particularly in resilience traits, we will be able to extend the growing zones over an even wider area – to the North with overwintering/cold tolerance, and to the South with water use efficiency/drought tolerance; Hastings *et al.* (2009) modelled the potential impact on biomass production of doing this and predicted an increase in overall energy production in the EU of 88% if drought and frost tolerance based from parental species was incorporated. These resilience traits are under active research at IBERS, Aberystwyth University, and will become targets for GS in the coming years.

With the speed of predicted climate change, and the associated increase in extreme weather events, it is critical that we future-proof this perennial crop. Commercial Miscanthus must stand for over 10 years and not only survive but yield regardless of the seasonal variability. We therefore need to optimise the use of our diverse germplasm in order to capture the traits which produce the highest possible yields, but also combine these with resilience traits to protect the crop against multiple extreme weather events over the lifetime of the stand, now and into the future.

The overall aims of breeding Miscanthus are to:

1. Develop varieties with higher biomass yields and improved quality characteristics.
2. Develop varieties for a range of climatic zones, focussing on the UK climate initially.
3. Ensure the crop can withstand the extreme weather events that will result from climate change.
4. Develop resilience to pests/diseases by breeding seed-based varieties (both intra-specific and inter-specific) to allow populations of plants to be grown as opposed to genetically identical monocultures.
5. Develop seed-based varieties to support a more rapid industry scale-up than would be possible with clonal material.

3.3 The current approach to Miscanthus breeding in Aberystwyth

A. Paired crossing. These crosses are performed in controlled environments in the UK in order to control flowering synchronisation (*M. sinensis* and *M. sacchariflorus* have diverse flowering times). These crosses go on to breeding nursery trials for assessment (stage 4 below). This approach was used to create our currently licenced varieties, but as GS improves our recurrent selection populations we expect paired crosses to become less important in breeding.

B. Population breeding. The current breeding approach, primarily focused on the generation of inter-species Miscanthus hybrids, is based on conventional phenotypic selection and consists of five stages:

1. **Creation of within-species synthetic populations.**

Leading germplasm from among our ~1500 wild collections are selected for key traits including high biomass, developmental and quality traits, and ability to generate excellent progeny. A limited number (typically 8) of our most promising plants are selected as parents for each synthetic population. To date we have established six synthetic populations representing different Miscanthus species and subtypes.

2. **Improvement of synthetic populations (recurrent selection).**

Each synthetic population is planted in crossing plots to enable polycrossing of all parental combinations. Seed is collected from each plant and large numbers (up to 1000 per population) of individuals are planted out in the field. After 3 years when the plants reach maturity, a small number (<10) of the best progeny are chosen based on mature plant phenotypic data, and these plants then become the basis of the parent population for the next recurrent selection cycle. Outputs of the recurrent selection populations may be evaluated as novel intra-specific hybrids.

3. **Generation of inter-specific hybrids (Optional).**

The selected parents from the recurrent selection populations are placed into new interspecific crossing plots, either with selected parents from another recurrent selection population or genotypes demonstrated to be outstanding interspecific parents.

4. **Breeding nursery trials.**

Seeds from the synthetic populations and inter-specific hybrid crosses are collected, and *ca.* 20-60 of the best progeny per maternal genotype are planted out in breeding nursery trials. When mature, the progeny with desirable traits are selected for evaluation as putative hybrids.

5. **Hybrid upscaling (intra- or inter-specific).**

Clones of both maternal and paternal plants are planted in seed production plots. The resulting hybrid seeds then go on to commercial evaluation; multi-location trials, agronomy development and assessment of biomass yield and quality.

3.4 Other Miscanthus improvement programmes

Europe: An intraspecific breeding programme with a focus on biomass quality traits for bioconversion in *M. sinensis* is based at Wageningen University & Research (WUR) in the Netherlands but has not yet produced any commercially available varieties. We regularly collaborate with WUR on Miscanthus, with a particular focus on multi-location trials across Europe (Lewandowski *et al.* 2016).

USA: The University of Illinois breeding programme is focussed on cell wall traits (relating specifically to improving the scope for Miscanthus as a liquid biofuel) and improving winter hardiness (a problem with Mxg that precludes significant expansion across USDA zone 5b). We actively collaborate with Illinois, most recently on sequencing the *M. sinensis* genome. Their analysis of germplasm has demonstrated that many Miscanthus varieties on the market are in practice Mxg; e.g. the clone Mxg 'Illinois' has the same origin as European Mxg (Dong *et al.* 2019).

Asia: There are a number of small scale and highly trait-targeted breeding programmes in China, South Korea and Japan, including:

- Chinese Academy of Sciences in Nanjing has a programme to breed saline-tolerant *Miscanthus* varieties suitable for large area of saline contaminated lands in eastern China
- South Korea – National Seoul University has collaborated with partners in Siberia to breed extreme-cold tolerant varieties.
- National Hokkaido University (Japan) has a programme aimed at producing varieties for contaminated land.

We actively collaborate with other Miscanthus breeding institutions on underpinning science, pre-breeding work and variety evaluation, and it is our view that as is the case for other crops, this offers significant advantages, both to variety development (e.g. with integrating specific traits once they are better understood), and for increasing the scope for expansion of the crop into new markets internationally. Each program has its own targets and will likely be complementary in the longer term.

The key achievements of the Aberystwyth Miscanthus programme to date are:

1. Collection and curation of the largest Miscanthus germplasm collection outside Asia.
2. The development of fundamental underpinning science on plant physiology including yield components, flowering, senescence, stress tolerance and cell wall characteristics.
3. Initiation of a breeding programme with this germplasm in accordance with International Good Practice, culminating in the licencing of varieties to a UK company and entry into CPVO registration trials within 15 years.
4. Collaboration in the international publication of the *M. sinensis* genome, and publication of the draft *M. sacchariflorus* genome with the Earlham Institute.
5. Development of Miscanthus agronomy, including that required for seed-based varieties.
6. Associated work on environmental aspects of the crop (e.g. carbon fluxes, land suitability, environmental tolerances).
7. International collaboration with other Miscanthus researchers and experimental breeders including in Europe, the USA, and Asia, evidenced by extensive publications.

3.5 International conventions on ethical use of germplasm

Any genetic resources collected since 1993 need to abide by the UN Convention on Biological Diversity (CBD) which was further elaborated in the Nagoya Protocol in 2010. The Nagoya Protocol provides a transparent legal framework for the effective implementation of CBD's third objective 'access and benefit sharing' (ABS). Both CBD and the Nagoya Protocol/ABS are transforming the way genetic resources are accessed and utilized, and are having a profound impact on conservation, biodiversity and the ethical use of genetic resources on a global scale. AU's Miscanthus genetic resources collection protocols and practices are consistent with the CBD's principles on safeguarding biodiversity, respecting conservation needs, and ABS. We have developed bilateral agreements with Chinese, Japanese, South Korean and Taiwanese Institutions covering access to the specifically collected germplasm for scientific evaluation and exploitation. We have been working closely with Defra's CBD and ABS related staff to ensure that all our collections are compliant with the principles, clauses and sprits of CBD and the Nagoya Protocol/ABS (in a process reviewed by Huang *et al.*, 2019).

Miscanthus collections that pre-date these agreements are widespread (e.g. ornamental specimens in botanic gardens, plants from experimental breeding) and the genetic origin of many of these is unclear. Naming conventions also add to the confusion e.g. types designated 'Miscanthus giganteus' exist with multiple ploidies (Dong *et al.* 2019), and the commercially planted triploid clone Mxg is marketed under a variety of names. Additional clones whose genetic origin is unclear are likely to enter the market in the near-term.

4 Integrating Genomic Selection into Miscanthus breeding

4.1 Background to genomic selection as a breeding approach

With the advent of next generation sequencing and the availability of sequenced crop genomes, genomics assisted breeding has transformed what is possible in plant and animal improvement programs. Previously selection was only possible from plant phenotypes, which might be influenced by maturity, the environment in which they are grown and the seasonal variation. However, once genomic trait associations have been established, GS can be applied, directly from the genomic DNA. The key benefits of this approach are a) that it allows traits of interest to be selected at the seedling stage, thereby reducing time and the costs associated with growing plants to maturity in the field, and b) that the effect of environmental conditions are excluded. Although a sequenced genome is not essential for GS, it helps to realise the full potential of the technology. Initially only limited crop genomes were prioritised due to the prohibitive costs of genome sequencing; as sequencing technology has improved, and costs come down, more genomes are becoming available and genomic breeding is no longer restricted to a limited number of high value crops. **With the availability of the Miscanthus genome (Mitros *et al.*, 2020) we believe that this is the perfect time to adopt GS technology in Miscanthus. Furthermore, we intend to combine this with speed breeding techniques in order to make the most genetic gain in the shortest possible timeframe.**

GS requires the rapid and reliable tracing of a selected subset of genomic markers for trait associations in successive generations of plants. The two components are therefore genomic markers associated with traits of interest and the plant populations on which the GS is to be applied. Genomic prediction (trait association) models have been implemented successfully in commercial breeding programmes for annual food crops such as maize, a close relative of Miscanthus, (Rice & Lipka, 2021) and wheat (Tessema et al. 2020). Creating a genomic prediction model requires a population of plants with well understood phenotypic characteristics (traits) to act as a training set. DNA is extracted from each plant in the population and molecular markers developed. The key requirements for developing an effective model are; a) a relevant training population; b) availability of suitable genomic markers; c) ability to undertake rapid genotyping at seedling stage; d) good phenotype data within the training population. GS removes the need to wait for the progeny to reach maturity, by using the trait-associated genomic marker information at the seedling stage. The predictions eliminate the need to wait for the large number of seedlings to mature in the field by allowing the best new recurrent parent plants to be selected using the rank ordered predicted trait values.

We have selected two recurrent selection pools in which to apply GS in Miscanthus, as these represent the two parental species (*M. sinensis* and *M. sacchariflorus*) which combine to generate the highest yielding hybrids such as the commercial crop Mxg. **The aim is to optimise each species group using GS in order to optimise the generation of high-performing wide hybrids in the future, similar to the A and B groups employed in elite F1 maize breeding.**

The application of GS in Miscanthus breeding would:

1. decrease in the time taken for a recurrent selection cycle from 3 years to 1 year
2. significantly reduce the number of progeny that need to be grown to maturity in this step of the breeding process
3. enable the integration of additional trait selection in the medium and long term based on an improved understanding of the Miscanthus genome, thus offering an effective breeding platform for the future.

4.2 Progress towards genomic selection in Miscanthus

There are a number of differences between Miscanthus and annual grain crops; the domestication process has only just begun and breeding programmes are comparatively small. Furthermore, the target traits are not those typically targeted in cereal crops and so are less well characterised, and the mature phenotype does not develop until the plant is 3 years old, which adds to the challenge of creating a training population. However, the genome sequences for Miscanthus species have recently become available, and their similarity to other C4 grasses in which GS has been successfully implemented (e.g. maize) provides additional confidence that GS could have a transformative impact in Miscanthus breeding.

Key to making accurate marker-based selections are the GS models. Miscanthus yield and resilience traits have complex underpinning genetics and are therefore difficult to select for in a breeding programme. For example, yield relates to both the length of the growing season, i.e. timing of establishment, flowering and senescence, and the stem components, height, thickness and number. It is therefore important to first establish robust genome trait relationships via statistical modelling. We have previously demonstrated successful model development in both a population of 138 *M. sinensis* genotypes (Slavov *et al.* 2014, Davey *et al.* 2017) and in Phase 1 we have analysed the data from a larger, multi species trial of 952 diverse genotypes.

Our first GS study in Miscanthus comprised a population of 138 *M. sinensis* genotypes (Slavov *et al.* 2014) and demonstrated that traits of interest including flowering time, senescence, stem diameter and tallest stem height were well predicted. The trait-associated markers developed for these trials were initially identified without a reference Miscanthus genome by alignment to the sorghum genome (using SAMtools). Many key traits are composites of multiple traits, e.g. yield is impacted by stem height, width, and number. Selection indices integrate multiple traits into a single value that the breeder can design to be a balance of a range of traits of interest. Selection on this multi-trait

Our background IP that we bring to the project therefore includes demonstration that:

1. Key selection traits have good predictive ability
2. GS can be undertaken with small training populations
3. Translating GS into our commercial Miscanthus breeding programme is feasible

selection index then selects all the traits of interest at once. This approach is routinely used in animal breeding but is still in its infancy in plant breeding. Following the demonstration that GS is a viable technology on multiple Miscanthus species, we developed selection indices (combining traits such as emergence, senescence and flowering time) that significantly improved the predictive ability of the yield models (Davey *et al.* 2017).

In Miscanspeed Phase 1, the GS analysis was expanded into a large trial, comprising 952 genotypes very diverse in their morphologies and original geographical locations, and including multiple species and hybrids. The plants have been genotyped and the markers mapped onto the recently published *M. sinensis* reference genome which has enabled the generation of a larger number of informative markers (using the Tassel GBSv2 software pipeline). The use of the Miscanthus reference genome allows us to better leverage the genome information to inform the GS work and to identify genomic markers significantly associated with traits of interest via Genome Wide Association Study (GWAS). With sufficient marker coverage, the genome positions of these markers can then be used to identify genes associated with the traits. Selecting on genomic information as opposed to phenotypic information is more robust as it is not susceptible to modification by the environment. For this reason, traits with high heritability are selected for use with GS.

Marker analysis revealed eight species groups within the 952 genotypes, and GS was successfully demonstrated for each of these separately. The traits investigated included yield, morphological traits important for yield, emergence, flowering and senescence, and quality traits such as moisture content, ash and lignin. Many of these traits are laborious and/or expensive to measure, making genomic prediction particularly attractive. These results have informed our decisions on which breeding populations and traits to target in Miscanspeed Phase 2, as the within-species groups are analogous to the recurrent selection populations we propose to use. Different traits will be optimised in the two synthetic populations, including stem height and senescence in *M. sacchariflorus* and stem number, leaf:stem ratio in *M. sinensis*. Furthermore, these data have been used to model the impacts of different marker numbers on GS efficiency which in turn impacts the selection of marker technology for our phase 2 project.

Summary of GS model development in Miscanspeed Phase 1

1. GS models have been established for multiple Miscanthus species using the newly available Miscanthus sinensis genome and have informed our decisions on the recurrent selection populations for Phase 2
2. Key traits have good predictive abilities and other potentially useful traits with good predictive abilities were identified
3. The results demonstrated that the training population sizes proposed for Phase 2 can give good GS predictive abilities
4. The data were used to model the impact of different marker numbers on GS efficiency to provide information for the selection of the marker technology for Phase 2
5. Selection indices have been demonstrated in Miscanthus species with a view to using it to implement multi-trait selection
6. Software infrastructure has been developed and is available for application in Phase 2
7. GS is a viable technology for our *M. sinensis* and *M. sacchariflorus* recurrent selection populations

4.3 Phase 2 implementation – integrating GS into Miscanthus breeding

Miscanthus breeding at Aberystwyth has been integrated with fundamental research on the crop in order to both domesticate and breed this wild genus into a commercial biomass crop within decades as opposed to the millennia taken by established crops such as wheat and maize. Breeding and research has been funded by diverse sources including BBSRC, commercial and EU and, to date, has involved partners in dedicated crossing and growing environments across Europe. In common with other crops, Miscanthus flowering is delayed in northern latitudes and crossing blocks are often situated closer to the equator. Furthermore, Miscanthus can take up to 3 years to reach maturity in the UK, a year more than in its optimal growing conditions. While flowering time diversity is a challenge for seed production, in this project we are using recurrent selection populations of *M. sinensis* and *M. sacchariflorus* in which flowering has been synchronised in previous generations.

A. Genomic Selection

To date, recurrent selection pools have been generated in Miscanthus by selecting 8 parents for polycrossing to generate the next generation of seed. 1000 seedlings are then grown to maturity and evaluated in the field to select the best 8 for the next round of polycrossing and so on. The evaluation trials have been performed in Germany as the plants reach maturity a year earlier there than they do in the UK where plants are generally considered to be mature by the end of year 3. Using GS in combination with speed breeding techniques we aim to complete the crossing and selection cycle within a year, and in the UK, summarised in Figure 1.

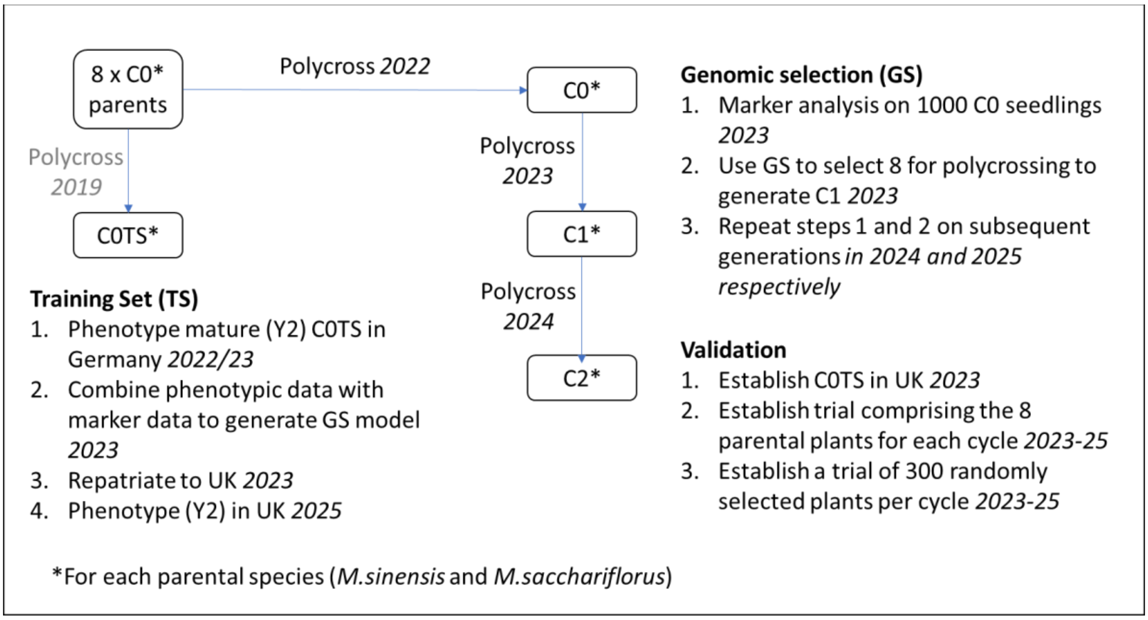

Figure 1. Summary of the GS cycle proposed in Miscanspeed Phase 2

GS requires a training set, a population of plants with genetic relevance to the breeding population, which are used to generate the GS model which is then applied to the breeding cycle. The current generation of both populations, designated C0TS for this project will be genotyped and phenotyped in Germany, where they will be mature in 2022, in order for trait associations to be made to train the GS model. In year 1, we will recreate this cross from the 8 C0sin and 8 C0sacch parents to generate C0 populations for GS. C0 seed will be planted in glasshouses in Aberystwyth and sampled for genotyping once they reach a sufficient size. DNA will be extracted from leaf material and genotyped. The GS model developed for sibling population C0TS will be applied to determine the 8

C0sin and 8 C0sacch selections for polycrossing to generate the next generation, C1, and this cycle will then be repeated.

The 8 C0sin and 8 C0sacch plants will be planted in the field in Aberystwyth for future evaluation, and the subsequent parental selections will be added annually. Concurrently a larger trial of approximately 300 progeny per group per cycle including the original training sets (C0TS) will be established to evaluate the genetic gain each cycle and retrain the GS model in the future as is standard in GS breeding programs (Figure 1).

B. Speed Breeding

There are three key elements that need to be optimised for speed breeding:

1. Rapid cycling (achieving flowering within a short growth period allowing for a truncated growth season due to selection via GS early in the growth season)
2. Flowering synchrony (achieving improved levels of flowering synchrony between diverse genotypes)
3. Seed production (achieving sufficiently high year 1 biomass production to produce high numbers of seed).

A key component of GS-accelerated breeding is the ability to undertake **annual seed-seed cycles**, with seeds produced in the autumn being sown in glasshouses overwinter and cultivated to mature flowering plants that flower and set seed the following year. Our current breeding practice is to send plants to Southern latitudes for crossing where the plants mature more rapidly than in the UK and seed set is reliable. This accelerated plant maturation allows the rapidity of GS in recurrent selection cycles to be fully exploited.

In Phase 1 we compiled the protocols required for the Sothern latitude work in collaboration with Energene Seeds Ltd. Protocols relating to the post-Brexit changes in procedures for movement of plant material between countries were also developed. These will be included as schedules to future legal agreements between Aberystwyth University and Energene Seeds Ltd.

A key limitation to plant breeding is the **synchronisation of flowering time** in parental plants in order to generate good seed set. During Miscanspeed Phase 2, the parental accessions will be grown in crossing blocks in the environments anticipated to optimise flowering synchrony on El Hierro in the Canary Islands. Plants will be monitored for growth and flowering, and meteorological stations will capture the associated climatic data. In Miscanspeed Phase 2 we will also replicate southern latitude environments in our controlled environment glasshouses (Venlos) in Aberystwyth. Initially we will modify two Venlo compartments at Aberystwyth to enable us to mimic the light and temperature variations that provide flowering synchronisation in El Hierro, and these will be adjusted annually as we incorporate the meteorological data from the crossing sites on El Hierro using the environmental monitoring equipment at the two locations targeted for *M. sinensis* and *M. sacchariflorus* respectively. This will provide data on the precise combinations of temperature and photoperiod to be simulated within glasshouses at Aberystwyth.

It is anticipated that the seed set from the outdoor crossing blocks in El Hierro will be superior to that in the glasshouse in Aberystwyth, but by the end of the project we aim to demonstrate that UK based seed production can be achieved sufficiently reliably to support the annual speed-breeding cycles that are required to fully harness the potential of GS within our recurrent selection populations.

In subsequent years the parents of the recurrent selection pools will be replicated and grown at alternative altitudes on El Hierro in order to determine and refine predictions of the growth trajectories that lead to flowering. In the Venlos we may also deliver the factors that are required to induce flowering in a way that differs to those in the natural environment (i.e. simulate an 'ideal' environment) including via altering the light spectrum, use of infra-red heat, and modifying humidity. **Our aim is to determine the critical factors that are necessary to produce flowering synchrony among our recurrent selection populations allowing them to be reliably replicated in controlled environments. We will optimise plant growth conditions for robust plant growth and monitor seed set in the CE at Aberystwyth.**

Project plan

We have developed a project plan for phase 2 of the project, the science component of which is based on the GS cycles illustrated in figure 1. WP1 consists of governance and management activities. Field trials (of the training set population and the recurrent selection progeny) comprises WP2. WP3 and WP4 cover genomic marker generation and GS modelling respectively. Accelerated maturation and crossing will be carried out in glasshouses in the UK (WP5) and Southern Latitudes (WP6). WP7 consists of knowledge exchange and commercialisation.

4.4 Breeding cycle time using genomic selection compared to conventional phenotypic selection

The genetic gain possible by integrating GS into the breeding programme is illustrated by the number of recurrent selection cycles possible within a fixed time period. For crosses carried out in 2022 and a conventional breeding approach based on phenotypic selection we would be assessing our first new selection in 2027, whereas we would be on our 5th selection cycle if GS was used in combination with accelerated plant maturation (Figure 2).

With conventional phenotypic selection, plants within our recurrent selection pools are grown to physiological maturity (2 years in Germany, 3 years required in UK conditions) before being assessed for traits of interest. The best plants are then used as parents for the next recurrent selection cycle. A key advantage of GS selection is that selections can be made at seedling stage, so reducing each cycle to a single year (Figure 2). Using phenotypic selection, crosses made in 2022 are then planted in the field in spring 2023 and assessed in spring 2025 when the best are selected (first selection). These plants are then crossed in 2025, with the resulting seedlings being planted out in spring 2026, for assessment and second selection in spring 2028. Using GS, crosses made in 2022 are assessed in spring 2023 and the first selection is made. These plants are then crossed in 2023, allowing the second selection to be made in 2024.

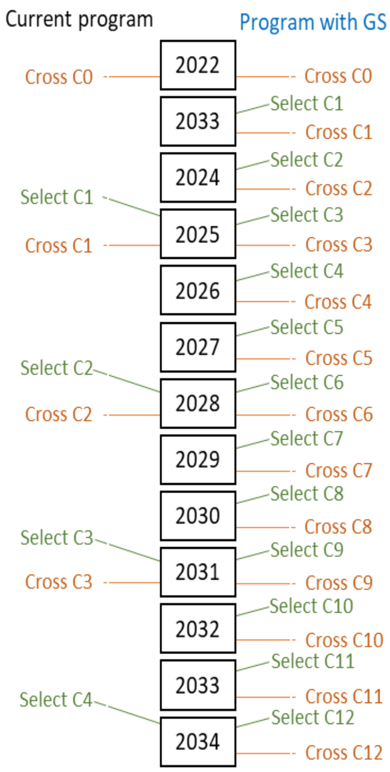

Figure 2. Comparison of conventional (current) breeding

5 Commercialisation

The approach taken in this project was to: a) review typical approaches to commercialisation and plant breeding and the nature of the assets within breeding programmes; b) review current and potential future assets within the AU breeding programme specifically; c) investigate the current and future market demand for these assets; and d) estimate the impact of commercialising the assets on the UK's ability to meet its biomass targets and combat climate change, and also on revenue generation to fund future breeding.

5.1 Plant breeding at Aberystwyth University

Aberystwyth University (AU) has an excellent track record in plant breeding and commercialisation of varieties across a range of crops including oats (licenced to Senova), forage grasses (Germinal), peas and beans (Wherry & Sons). IBERS is the UK market leader in winter and spring oats (IPO, 2016). Varieties have been marketed by Senova (previously Semundo) since the 1980's. This includes both husked and naked oats. **IBERS varieties are estimated to make up 83% of the UK seed area of winter oats. Total UK planted areas for oats were 210,000 ha in 2020, with a market value of £150 million (Defra, 2021b). IBERS forage grass varieties dominate the UK market; estimated to be 39% of the UK market share for grass and herbage, with the next largest being DLF with 14.9% (IPO, 2016). With our unique expertise in the commercial breeding of diverse crops, including of perennial grass species, we are ideally placed to bring novel Miscanthus varieties to market for the UK.**

The University has an extensive collection of Miscanthus genotypes which forms the basis of its breeding programme. In the early 2000's a review of the diversity of the germplasm available determined that much of the germplasm held by botanical gardens, institutes, horticultural suppliers and private collections was of unknown origin, having been collected many years previously. Three potential problems arise from this. Firstly, the germplasm might not include the full range of potentially desirable traits that are exhibited by the plant in its native habitats, so collection of more wild source germplasm was desirable in order to capture key traits such as biomass yield and tolerance of biotic and abiotic stresses. Secondly, lack of data on the environmental envelope from which the plant was collected would lead to uncertainty about its potential suitability for UK conditions. Thirdly, the issue of ownership and clarity of rights and benefits also arises. Consequently, a number of collection trips (2006-2011) were organised. This has resulted in a collection of 1500 accessions from 500 sites across Eastern Asia, including China, Japan, South Korea and Taiwan. Sites were specifically chosen to ensure a range of environmental envelopes. Significant elements of this work were undertaken in conjunction with Ceres (a US plant science company with an interest in Miscanthus breeding). Exploratory crosses, phenotypic characterisation, a formal breeding programme and the development of seed production techniques followed, and has culminated in the exclusive licencing of 10 varieties to Terravesta in 2020, with 6 varieties undergoing DUS (distinctness, uniformity and stability) tests at the Community Plant Varieties Office (CPVO). The examination period on these varieties is expected to culminate in their successful registration in the first quarter of 2022.

5.2 Current and potential future assets in the Aberystwyth Miscanthus breeding programme

During phase 1 we undertook a review of models for funding plant breeding, the nature of the assets involved in Miscanthus breeding, and the likelihood of market failure, summarised in Appendix 3. We do not regard the GS models we would develop during a phase 2 project as assets we could commercialise, as they would be specific to the germplasm populations on which they were based, and to the (UK) environment for which the models are developed. Rather, the innovation of GS models would accelerate the production of new plant varieties for commercialisation.

The Miscanthus breeding programme itself, comprising its foundation germplasm, its existing populations, putative hybrids under development, and expertise are clearly a significant asset. Given the high likelihood of market failures (environmental externalities and public good) associated with Miscanthus breeding, the University wishes to retain this asset as a public good. Some aspects of the use of germplasm remain subject to an agreement with a third party.

We have made rapid progress towards plant variety registration, 10 varieties were licenced to Terravesta in 2019. The varieties which have pending applications with the CPVO and in the UK as plant varieties are detailed in Appendix 2. All are progressing as expected and within the CPVO and UK procedural time frames. It is expected that a decision on grant will be made in 2022 on some of the varieties filed.

The potential assets relating to the proposed project and our current programme include:

- Genomic selection models
- The breeding programme itself, including associated germplasm and expertise.
- Existing plant variety rights held and potential future varieties

Asset protection

Aberystwyth Miscanthus Varieties are protected through the filing of Plant Variety Rights which prohibits anyone else using our Miscanthus Varieties without our permission for 1) production or reproduction, 2) selling or offering for sale, 3) altering the variety so it can be propagated, 4) exporting or importing or 5) keeping stock of the Miscanthus Variety for any reason. Through Aberystwyth University's Research, Business and Innovation department we monitor the Miscanthus landscape to ensure that to the best of our knowledge, no third party breaches our plant variety rights. If a suspected breach is identified, further due diligence is carried out and enforcement action taken if found to be a breach of the University's plant variety rights. The increased knowledge of combinations and locations of genomic markers on the genomes we develop using GS and the sequencing pipelines established in Miscanspeed Phase 2 would make protection through genetic fingerprinting more robust, cheaper and more straightforward (in terms of our ability to conclusively prove that an infringement occurred). The use of registered trademarks to protect variety brand names will also be considered as part of the overall intellectual property strategy in future.

5.3 Current market demand for assets

During phase 1 we undertook a review of market supply and demand in the UK. Information on supply side providers is given in Appendix 4. From the supply side perspective, the current UK market for Miscanthus is small, with only 2 companies (Terravesta and Miscanthus Nursery Ltd, MNL) providing commercial planting material (ornamental varieties are widely available). The total planted area in England in 2020 was stated by Defra to be 8,286 ha (Defra, 2021) and as shown in Table 1, is not increasing at a significant rate. Total areas in the devolved nations are assumed to be small (e.g. we estimate <100ha in Wales).

Year	2015	2016	2017	2018	2019	2020
Area (ha)	6,905	7,057	7,366	7,149	8,171	8,286
95% confidence interval	514	526	1,097	1,290	1,275	2,046
Number of growers	409	361	787	767	731	708

Table 1. UK plantings of Miscanthus/UK land area under Miscanthus cultivation 2015-2020

Current UK demand

The current demand for Miscanthus biomass significantly exceeds supply; the main supplier in the UK (Terravesta) supplies an average of 50,000 tonnes/year from their contracted growers to end users. Approximately 95% of this is to whole bale power stations, with 5% into other markets including briquettes and equine bedding. Terravesta state that their existing end user market (i.e. whole bale power stations) could take 500,000 T/year. There are 4 whole bale power stations in England, burning largely cereal straw; Defra (2021) report data from Ofgem of 888,000 tonnes straw burnt in 2020. Whilst Drax no longer burn Miscanthus, as an indication of potential market scale, Drax imports approximately 7 million tonnes of wood annually. Other current or near-term end uses are likely to be considerably smaller (e.g. a manufacturing facility might take 50,000 tonnes/year) and therefore have less impact on royalty revenue, but will likely be key to the uptake of Miscanthus by potential growers local to these facilities. Animal bedding is another significant near-term market; whilst currently supplied largely by wheat straw, increasing competition for straw from whole bale power stations (each with a typical capacity of 250,000 tonnes/year) will significantly impact straw prices and is already leading to Miscanthus growers supplying local bedding markets. Total UK demand for straw for animal bedding is estimated to be approximately 6 million tonnes (with a total of 12 million tonnes of cereal straw produced in the UK according to Copeland & Turley, 2008).

Current international demand

As outlined in section 2.1, the potential land areas available for perennial biomass crops are enormous (7-47 Mha estimated by Forsell *et al.*, 2016, Ruiz *et al.*, 2015, Deppermann *et al.*, 2016). Existing planted areas and supply chains are well developed in certain countries (e.g. the company Miscanthus d.o.o. has 100ha of rhizome nursery in Croatia of Mxg 'Illinois', and plantings are increasing in Hungary, Austria and the Western Balkans). An Aberystwyth variety, Bia, is undergoing registration procedures in Moldova. The more favourable economics of clonal planting in countries with larger land areas and lower labour costs may limit the near-term demand for seed-based varieties, but the risks that would result from lack of pest and disease resilience are significant. Whilst many named cultivars are sold, it is likely that the majority of these are triploid Mxg (Dong *et al.* 2019); introducing novel clonal varieties would therefore be beneficial in the near-term. We expect demand for future varieties to follow a similar pattern to that in the UK.

Key findings:

- Current biomass demand from whole bale power stations in the UK outstrips supply by > 10 fold, but to date this is not resulting in significant increases in the total planted area.
- The resilience risks resulting from future reliance on small numbers of clonal Miscanthus varieties are not widely recognised by stakeholders. More diverse clonal options and seed-based varieties are required to limit risks from pests and disease, as is common practice in willow.
- As countries develop their policies for reaching net-zero, international demand for Miscanthus varieties will be significantly higher than that in the UK market alone, and there are likely to be relatively few varieties available from other breeders.

5.4 Impact of exploiting these assets on UK biomass production and future commercial strategy

Future UK market scale

The key factors influencing likely future size of the UK Miscanthus market (which in turn is assumed to drive sales of AU Miscanthus varieties and therefore revenue income) are:

1. Policy/fiscal measures introduced in order to stimulate uptake by potential growers.
2. Number and scale of companies developing to meet any resulting demand in planting.
3. Competition between suppliers in the UK and beyond (influencing the availability of planting material).
4. Success of seed-based hybrids; required to both safeguard market against resilience risks from clonal material, and to prevent availability of planting material becoming a limiting factor.

During phase 1 we examined these variables within the UK as summarised in three scenarios:

Stagnant: Trajectory of a 10% increase in planted area per year from predicted 2022 levels. No replanting of existing stocks but also no reversion to non-biomass crops. Loosely based on current markets and existing absence of policy incentives for biomass planting.

Moderate: 20% increase in planted area per year from predicted 2022 levels, with additional entrants to the market also planting clonal varieties in response to increased availability and government subsidies. Existing AU varieties planted as clones from 2025, making up an increasing market share of plantings by the licence holder. Replanting of existing biomass crops from 2030 owing to higher performing new varieties becoming available. Loosely based on an assumption of planting incentives under future agricultural subsidy regimes and/or a substantial fiscal incentive favouring UK produced biomass (e.g. via carbon pricing or valuation of ecosystem services) leading to an increase in companies offering planting and harvesting services.

Accelerated breeding: As above, but with seed-based varieties from a GS-accelerated breeding programme becoming available in 2032. These would have a more rapid uptake than clonal varieties owing to a) higher yield and/or greater viable growing area, b) seed-based providing added scale up capacity, c) higher volume markets resulting from better quality varieties.

Important considerations

Our calculations indicate that none of the above scenarios allow the UK to meet the UKCCC target for perennial biomass crop planting rates of 30,000ha/year by 2035 (assuming that 50% of this is Miscanthus). The current trajectory (stagnant) also fails to meet the UK's 2050 biomass targets. As evidenced by Defra (2021), the planted area of Miscanthus has remained relatively constant over the last 5 years, despite a consistent marketing effort by companies offering Miscanthus planting and supply chain services. With predicted UK plantings in 2022 of around 500ha (350ha Terravesta, assumed additional rhizome sales from Miscanthus Nursery Ltd), and an optimistic potential rate of expansion from this point, the UKCCC 2035 target seems unrealistic under any set of conditions, and analysis of the total carbon removal possible (i.e. using a metric of the cumulative tonnages of biomass produced as opposed to annual increases in planted are a) is warranted. Capacity to meet 2050 targets is contingent on early and significant investment across the biomass supply chain and in downstream facilities (i.e. carbon capture and storage infrastructure).

Whilst the limiting factor in the short term is willingness amongst farmers to grow the crop, in the medium term, availability of planting material is likely to become a key problem (assuming that clonal propagation remains the principle means of area expansion). Lack of variety choice might also limit uptake and would increase risk. The earliest likely point of entry into the market of varieties from a GS-accelerated breeding programme starting in 2022 is 2032 (although as the synthetic populations have already undergone improvement this could be sooner), and we would expect these to lead to a significant and rapid increase in planted areas from this point, given their likely superior performance and the relative ease of producing planting materials. We would expect 2050 planted area targets to be easily reached in this scenario.

Future commercial strategy and the impact of implementing genomic selection

As discussed in section 3, plant breeding programmes are long term investments, with costs typically around £200,000 - £2million/year. New varieties typically take 12-15 years to come to market. However, the return on investment for breeding is estimated to be 40:1, compared to 5:1 for fundamental research and 15:1 for more applied research (DTZ, 2010). The same report indicates UK royalty income across all crops to be approximately £40m pa. The current lack of maturity in the Miscanthus market means that private investment at the scale required to support significant breeding activity is not realistic. Furthermore, *"climate change is a result of the greatest market failure the world has seen"* (Nicholas Stern, 2006). Biomass is key to the UK Government's climate ambitions as it provides the feedstock for over 90% of engineered GHG removal in 2050 scenarios. As such, public support for perennial biomass crop breeding is key in the short-medium term to mitigate risks. If biomass policy leads to the significant increases in the annually planted areas, the inherently slow multiplication rates resulting from rhizome-based planting systems mean that a shortfall in planting material could occur, further highlighting the importance of developing seed-based varieties.

We would expect that marketing and sale of propagation material (rhizomes and seeds) to be carried out by private sector companies (e.g. those in Appendix 4 or new entrants). As such, royalty income from planted areas will be our key income stream in the medium-long term. Our target is for UK royalty income to cover one third to half the total costs by 2035, with non-UK royalty income making up an additional one third, and remaining funding being from public sources, reflecting the societal imperative to combat market failures relating to climate change. The key risk to achieving this aim is the lack of growth in the Miscanthus market (as illustrated in Table 1). Given the land areas available in other countries, sales of Aberystwyth varieties outside the UK will be key to future revenue income; this is not unrealistic given that a key stage of variety development is multi-location trials in several countries which has the effect of stimulating interest and demonstrating suitability in those environments. As such, Miscanthus represents a significant export opportunity we would seek to exploit.

GS will assist this aim in three key ways. Firstly, by accelerating the rate of genetic gain, new varieties will generate higher tonnages (with royalties being based on tonnes of biomass harvested). Secondly, the use of GS will make it significantly easier to meet the uniformity requirements for CPVO registration (something which is problematic with the relatively undomesticated germplasm that constitutes the parents for our current paired crosses that are currently undergoing registration). Seed based populations that meet uniformity requirements will allow rapid increases in the planted area. Thirdly, we can expect a faster rate of variety development, including the incorporation of resilience characteristics that allow further expansion of the planted area. As a result, implementing GS will accelerate and increase the amount of royalty income that can be reinvested in breeding.

The choice between exclusive and non-exclusive licencing depends on market maturity, number of companies operating in the market, and the market readiness of the variety (as discussed in Appendix 3). Changes in these factors will be taken into account when determining future licencing strategy.

A range of sources of finance support science at lower technology readiness levels and in associated areas of work that are necessary to support the rest of the Miscanthus supply chain, as detailed in Appendix 5. Pre-breeding work, genomics and trait analysis, and policy related work will also require ongoing public funding. Joint public/private initiatives (e.g. InnovateUK) are ideally suited to addressing near-market issues (e.g. agronomy) and private sector buy in helps ensure rapid translation of results into commercial practice, and we intend to continue work of this type independently of breeding.

Locations and scales of future markets

Whilst the primary aim of our Miscanthus breeding programme is to develop varieties suited to the UK market, in terms of future royalty income, European and International markets are likely to grow in importance, for two key reasons; a) because of the potential land areas available, as indicated in section 2.1, and b) the scope to breed in additional resilience traits to Miscanthus that increase the planted areas available. On this latter point, whilst the currently planted Mxg hybrid is relatively resilient to both drought and low winter temperatures, the potential impacts of future climate change must be taken into account when considering breeding future varieties, both for the UK market and for international exploitation. As discussed in section 3.2, **Hastings *et al.* (2009) demonstrated an 80% reduction in energy production and carbon mitigation by 2080 if Mxg was grown, but if genes for drought and frost tolerance were incorporated (with tolerances based on those found in Miscanthus parental species) the overall energy production could increase by 88%. Thus whilst Mxg is suited to current conditions, breeding is key to the future use of the crop and its capacity to contribute to climate change mitigation.**

Economic multipliers and the wider supply chain

The wider economic impacts associated with increasing supply of Miscanthus have not been analysed in this project as they are assumed to be undertaken by commercial operators. However, **Terravesta figures indicate that if 1500ha of Miscanthus rhizome were planted in 2022, the total establishment supply chain cost is *c.a.* £1.75 million**. This excludes any costs for land preparation and ongoing agronomy.

Potential for diversifying Miscanthus varieties available in the UK and likely competition to Aberystwyth varieties

We recognise that particularly in the short term (<10 years), Mxg and other clonal varieties could usefully supply significant volumes of the UK market, potentially in combination with the CEED encapsulation technology licenced by New Energy Farms. However, in order to maintain confidence in the market and to allow consideration of future disease risk, it will be important to ensure that genetically identical cultivars are not marketed under different names, and so some regulation is needed in this area. **There is considerable scope to diversify the number of clonal varieties available, and in terms of safeguarding the industry against crop losses from pests and disease, measures to promote diversity are crucial; in the short term this would be via planting mixtures of clones as is commercial practice for willow, and in the longer term via planting of populations of seed based hybrids, which are inherently more resilient.**

The scope for shared risk and multiple intervention points to further accelerate variety development

Plant breeding is an inherently slow process (e.g. 12-15 years for a new variety), but it is also a pipeline of development, with new varieties becoming available on a regular basis due to ongoing activity. GS will significantly accelerate the genetic gain achieved in the recurrent selection stage of breeding allowing a cycle to be undertaken annually rather than every 2-3 years as at present. Further interventions could also accelerate later stages in the breeding programme. This might include support for hybrid development and assessment, support for multi-location pre-commercial trials enabling larger numbers of putative varieties to be tested, investment in seed production facilities, and optimised agronomic practices. Owing to the relatively small scale of the current breeding programme and the costs associated with each step, they are typically carried out sequentially. However, **given the urgency with which the UK needs to scale up biomass production, serious consideration should be given to a shared-risk model that allows these stages to occur concurrently in order to further decrease the timescale for new variety development.**

6 Final summary

During phase 1 we:

- Developed the approach to GS that will be required in our commercial breeding programme, tested some of its key limitations, and demonstrated that it has a high likelihood of success for key species and traits of interest in the generation of future Miscanthus varieties
- Planned implementation of phase 2, developed protocols to facilitate speed breeding, analysed logistics of populations and plant movements required.
- Reviewed our assets, approach to commercialisation, current and future markets.

Key conclusions

1. **UK biomass demand outstrips domestic supply by several orders of magnitude**, and has done for many years. Given UK policy commitments on the role of biomass in meeting net-zero carbon emissions, demand will likely continue to increase. Policy intervention seems necessary to stimulate domestic production and would have significant economic and environmental benefits beyond decarbonisation.
2. Whilst in the short term, moderate increases in planted area could be met by clonal material (assumed to be largely *Mxg*, with a handful of cultivars from other countries and a small market share of Aberystwyth varieties), **significant and rapid expansion will require novel technologies and crop diversity**, including seed-based hybrids, both in order to meet the volumes of planting material required, and to limit the resilience risks that would result from reliance on a single clone as the UK's climate changes.
3. With the likelihood of rapid increases in demand in the near future, **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.
4. GS-accelerated breeding of Miscanthus by itself will be insufficient to meet the UKCCC planting targets. **Multiple interventions across the Miscanthus and willow supply chains will be required for biomass to deliver its role in net-zero and to meet the UK Government's legal commitments.**

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Appendix 2 – CPVO registration search

A search of the CPVO register carried out in December 2021 showed 16 varieties with rights granted, all of which are ornamental. A further 17 varieties are under active application. Of these, 7 are Aberystwyth varieties intended as biomass crops, with the remaining 10 being ornamental varieties. A check to see if varieties refused, terminated or withdrawn were biomass crops or ornamental was not undertaken.

Denomination	Species	Grant number	Status	Applicant(s)	Application date	Application number	Ornamental
Aphrodite	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	27/11/2020	20203045	
Artemis	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	27/11/2020	20203043	
Astraea	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	24/12/2018	20183177	
Atropos	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	24/12/2018	20183176	
Bia	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	29/11/2019	20193246	
Boreas	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	27/11/2020	20203044	
Brontes	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Active application	Aberystwyth University; Ceres Inc.	27/11/2020	20203046	
EMPMIS03	Miscanthus sinensis (Thunb.) Andersson		Active application	Piro Newplants B.V.	16/10/2020	20202554	yes
Fire Dragon	Miscanthus sinensis (Thunb.) Andersson		Active application	Christel Lewandowski-Menzel; Klaus Menzel	13/03/2019	20190682	yes
Lady in Red	Miscanthus sinensis (Thunb.) Andersson		Active application	Krzysztof Slowinski	16/10/2020	20202557	yes
Nica 20	Miscanthus sinensis (Thunb.) Andersson		Active application	Kwekerij Mesker	17/11/2020	20202900	yes
Red Zenith	Miscanthus sinensis (Thunb.) Andersson		Active application	Brian Robinson	30/03/2021	20210912	yes
Rica 20	Miscanthus sinensis (Thunb.) Andersson		Active application	Kwekerij Mesker	17/11/2020	20202899	yes
Sica 20	Miscanthus sinensis (Thunb.) Andersson		Active application	Kwekerij Mesker	17/11/2020	20202901	yes

Silver Charm	Miscanthus sinensis (Thunb.) Andersson		Active application	Artur Maj	03/05/2021	20211215	yes
Sunlit Satin	Miscanthus sinensis (Thunb.) Andersson		Active application	Brian Robinson	31/03/2021	20210947	yes
VICA 21	Miscanthus sinensis (Thunb.) Andersson		Active application	Kwekerij Mesker	11/10/2021	20212547	yes
Andenken an Ernst Pagels	Miscanthus sinensis (Thunb.) Andersson	48574	Granted	Gerhard Mühring	09/06/2015	20150862	yes
Ards Angel	Miscanthus sinensis (Thunb.) Andersson	48569	Granted	Johannes Nicolaas Mesker	22/12/2014	20143538	yes
Boucle	Miscanthus sinensis (Thunb.) Andersson	57849	Granted	Artur Maj	11/09/2018	20182335	yes
Brazil	Miscanthus sinensis (Thunb.) Andersson	48570	Granted	Johannes Nicolaas Mesker	22/12/2014	20143539	yes
EMPMIS01	Miscanthus sinensis (Thunb.) Andersson	48575	Granted	Piro Newplants B.V.	20/04/2015	20150874	yes
EMPMIS02	Miscanthus sinensis (Thunb.) Andersson	54917	Granted	Piro Newplants B.V.	29/01/2017	20170249	yes
Gold Bar	Miscanthus sinensis (Thunb.) Andersson	24450	Granted	Sunny Border Nurseries Inc.	17/11/2003	20032132	yes
Gold Breeze	Miscanthus sinensis (Thunb.) Andersson	42376	Granted	Maurice Horn; Mike Smith; Scott Christy	20/09/2012	20121985	yes
Ibiza	Miscanthus sinensis (Thunb.) Andersson	48571	Granted	Johannes Nicolaas Mesker	22/12/2014	20143541	yes
Little Miss	Miscanthus sinensis (Thunb.) Andersson	51518	Granted	Christel Lewandowski-Menzel; Klaus Menzel	31/08/2016	20162103	yes
Little Zebra	Miscanthus sinensis (Thunb.) Andersson	24951	Granted	Hortech Inc.	02/06/2003	20030776	yes
Lottum	Miscanthus sinensis (Thunb.) Andersson	29011	Granted	Geert Heinemans B.V.	17/08/2006	20061707	yes
Navajo	Miscanthus sinensis (Thunb.) Andersson	48572	Granted	Johannes Nicolaas Mesker	22/12/2014	20143542	yes
NCMS2B	Miscanthus sinensis (Thunb.) Andersson	54365	Granted	North Carolina State University	01/08/2017	20171898	yes
Polonus	Miscanthus sinensis (Thunb.) Andersson	58115	Granted	Artur Maj	19/10/2018	20182649	yes
Yaka Dance	Miscanthus sinensis (Thunb.) Andersson	48573	Granted	Johannes Nicolaas Mesker	22/12/2014	20143543	yes
Cute One	Miscanthus sinensis (Thunb.) Andersson		Refused	Johannes Nicolaas Mesker	22/12/2014	20143540	yes
Parachute	Miscanthus Andersson		Refused	Leenen Innovation B.V.	25/08/2003	20031397	-
Silverstripe	Miscanthus sinensis (Thunb.) Andersson		Refused	Kwekerij de Morgen V.O.F.	07/06/2004	20041040	-
	Miscanthus sinensis (Thunb.) Andersson		Refused	Bakhuijzen Companie B.V.	16/09/2010	20101842	-
America	Miscanthus sinensis (Thunb.) Andersson	30724	Terminated	Overdam Planteskole	06/06/2008	20081266	-
Apache	Miscanthus sinensis (Thunb.) Andersson	37274	Terminated	Teresa Foszczka	20/12/2010	20102855	-

MAF 0109	Miscanthus sinensis (Thunb.) Andersson	33378	Terminated	Sören Vodder	17/06/2009	20091129	-
Mobri	Miscanthus sinensis (Thunb.) Andersson	45562	Terminated	Michael Merz	03/04/2014	20140918	-
Mysterious Maiden	Miscanthus sinensis (Thunb.) Andersson	31625	Terminated	JACK WEISKOTT; JACK WEISKOTT	30/06/2008	20081514	-
NCMS1	Miscanthus sinensis (Thunb.) Andersson	54364	Terminated	North Carolina State University	01/08/2017	20171897	-
Supstripe	Miscanthus sinensis (Thunb.) Andersson	26394	Terminated	Darrell R. Probst	01/09/2006	20061775	-
Aperitif	Miscanthus sinensis (Thunb.) Andersson		Withdrawn	Beate Zillmer	11/12/2012	20122357	-
Aperitif	Miscanthus sinensis (Thunb.) Andersson		Withdrawn	Reinhard Meier-Zillmer	13/09/2010	20101773	-
Aphrodite	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Aberystwyth University; Ceres Inc.	24/12/2018	20183178	-
Artemis	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Aberystwyth University; Ceres Inc.	24/12/2018	20183175	-
Athena	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Terravesta IP Ltd.	28/11/2018	20183090	-
Boreas	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Aberystwyth University; Ceres Inc.	29/11/2019	20193249	-
Brontes	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Aberystwyth University; Ceres Inc.	29/11/2019	20193247	-
Feuerwerk	Miscanthus sinensis (Thunb.) Andersson		Withdrawn	Beate Zillmer	11/12/2012	20122358	-
Mica 06	Miscanthus sinensis (Thunb.) Andersson		Withdrawn	Johannes Nicolaas Mesker	02/10/2019	20192544	-
MSU MFL1	Miscanthus x giganteus J. M. Greef & Deuter ex Hodk. & Renvoize (M. sacchariflorus x M. sinensis)		Withdrawn	Mississippi State University	15/06/2012	20121264	-

Appendix 3 – review of typical approaches to commercial plant breeding

Historically, plant breeding in the UK and other countries was a public endeavour. During the 1980s most of the public breeding programs were sold or arrangements were made for near market costs to be absorbed by commercial companies. Breeding for the commercial market is now generally undertaken via one of the following models:

- Commercial breeding. For crops with sufficient volumes of annual seed sales globally, breeding can be financed largely via reinvestment of seed company revenues. Examples include some of the world's largest seed companies such as KWS (maize, sugar beet) and Limagrain (cereals, maize, oil seeds). KWS state that their 2020/21 investment in breeding was 232 million euros.
- Company collaborations. Programmes undertaken by several companies in collaboration (e.g. the UK seed company Elsoms collaborates with French and German companies on maize and wheat varieties).
- Public sector breeding with sponsorship arrangements for variety rights. Companies invest in breeding programmes based in public institutes, within a defined scope, in return for exclusive rights to new varieties. Aberystwyth University currently operates its oat breeding programme with Senova using this model. This approach works well for crops with relatively limited market size in their target countries, and where supply chain companies are of a scale where it is realistic for them to commit finances to a breeding programme for periods in excess of 5 years.
- Public sector breeding with open competition for new variety rights. Limited availability of finance prevents this model operating at scale, hence it is typically a precursor to one of the other financing models.
- Public sector breeding and marketing. Rarely undertaken now in the UK, but was the mainstay of many crops (e.g. Maris potatoes). Remains an option for orphan crops.

Significant 'pre-breeding' work is also undertaken, in the UK this is largely via public breeding institutions. The aim of this work is to analyse traits that are not present in the germplasm underpinning commercial breeding programmes, often in order to bring in diverse traits that are not present in elite varieties. The Defra funded Genetic Improvement Networks (GIN) are an example of this; experts work on genetic improvement of specific crops (wheat, field and leafy vegetables, pulse crops and oilseed rape). Each network has breeding industry representation and is aimed at characterising pre-breeding material in relation to stress and resilience traits.

Breeding involves significant financial risk (breeders might commonly work with over 10,000 crosses to develop a single commercial variety over a long time period (e.g. 15 years of development and testing before a variety is on a recommended list) as discussed by the Intellectual Property Office (IPO, 2016). The IPO estimate that levels of investment to maintain a breeding programme at between £200,000 and £2 million/year. However, the return on investment for breeding is estimated to be 40:1, compared to 5:1 for fundamental research and 15:1 for more applied research (DTZ, 2010). The same report indicates UK royalty income across all crops to be approximately £40m pa.

The currently planted varieties of Miscanthus (triploid Mxg and more recently Athena) are not registered and protected (and therefore do not result in any royalty payments to AU or have restrictions on use). The lack of royalty income accruing from existing sales means that commercial breeding is not a near term prospect; new varieties are therefore required to finance future breeding in addition to being required to expand the UK planted area.

In general, commercial plant breeding is financially constrained by two key factors. Firstly, revenue is limited by the amount of land dedicated to the crop. Given the need to maintain UK food supplies, Miscanthus should only be grown on land less suited to food production, estimated to be up to approximately 1.4 million ha, so this limits potential revenue income for breeding. Exporting varieties can extend the opportunity, and given that Aberystwyth is clearly a market leader in Miscanthus breeding, we would aim for this to be a significant element of future revenue. Secondly, the economic health of plant breeding is linked directly to that of the growers and producers. Fluctuations in commodity prices therefore will impact on revenue generation (and given a finite land area, fluctuations in markets for other crops will impact on planted areas of Miscanthus and therefore revenues).

Production and sale of propagation material (rhizomes and seed): As stated above, public sector breeding and marketing is a potential option. However, given that large scale seed production is best carried out in southern latitudes and specialist seed production companies exist, we would expect this activity to be better undertaken by the private sector. Similarly, the Western UK is not ideal for rhizome production, and as such we anticipate this activity to be best carried out by a suitably located company, as occurs at present in Europe. As such, Aberystwyth University does not intend to market and sell Miscanthus varieties directly, rather we anticipate licencing agreements in return for royalty income.

Exclusive versus non-exclusive licences: The choice of licencing model depends on three key issues:

1. Overall market maturity: in a situation where farmers/growers are already well aware of the benefits of the crop and relatively little marketing is required on the part of companies with access to varieties, non-exclusive licencing may be possible. However, if significant company investment is required to develop markets, it is reasonable for companies to demand exclusive licences.
2. Number of companies operating in the market: if the market is well established and multiple companies exist with the capacity to exploit a new variety, non-exclusive licences may be appropriate, but if there are few potential licensees then incentivising a single company to invest and support the technology is preferable.
3. Market readiness of the variety: if the variety has already undergone CPVO trials and is ready to be marketed as a variety, non-exclusive licencing may allow faster increases in planted areas, but if the variety has not yet been registered and/or seed production facilities are not developed, companies will likely require exclusive rights in order to justify investment.

The need for public investment in plant breeding

Market failures in relation to plant breeding are well documented (DTZ, 2010, Defra 2002), both in terms of the provision of public goods and the existence of environmental externalities.

Provision of public goods: These are the co-benefits arising from a product that are accrued by someone other than its producer. In the example of domestically produced biomass, the co-benefits to society would include improved flood resilience, biodiversity and soil carbon sequestration. Whilst it is difficult to attribute economic values to public goods, the economic value of avoided flooding alone that accrues from planting perennial energy crops is thought to be between £14/ha/year and £1525/ha/year depending on location (Holder *et al.*, 2019; Donnison *et al.*, 2020). It is important to note that if biomass is imported as opposed to grown in the UK, these public goods do not accrue in the UK. Clearly, the avoided CO_2 emissions that result from using bioenergy crops are a highly significant public good that is accrued regardless of whether biomass is imported or domestically grown, and the UK carbon values in 2021 are between £122 and £367/tonne CO_2 (BEIS, 2021).

Environmental externalities: These are side effects of the industry concerned, that are paid for by society rather than the market. For example, in the case of perennial biomass crops specifically, higher economic returns to growers would result from growing the crop on high quality land rather than marginal land. This is clearly not a desirable approach for society, and as such the focus in the Aberystwyth breeding programme is to develop varieties that yield well on marginal land and do not require fertiliser inputs.

The yield and productivity benefits from plant breeding also have indirect benefits beyond economics, as reviewed by Noleppa (2016). These include a) increased availability of commodities, b) improved trade balance, c) avoided CO_2 emissions (assuming that an increased yield/ha reduces pressure to convert land to agricultural purposes).

The nature of assets and intellectual property within plant breeding

Plant varieties are a form of intellectual property, protected by law in the UK and Europe as Plant Variety Rights (PVR) or Plant Breeders Rights (PBR). Royalties for annual crops are collected via two systems in the UK; a charge on the cost of seed or propagation unit at point of sale, or by royalty area collection (RAC). Which method of collection is decided by the breeder at the time of entry to DUS testing. In the UK, royalties are collected by the British Society of Plant Breeders (BSPB, 2021). RAC was developed with the intention to introduce a unified royalty rate for certified and farm-saved seed and is characterised by farmer declarations of areas sown. For perennial crops, an additional royalty collection mechanism based on declared tonnages harvested (i.e. end product licence fees) can be built into licence agreements (and this is part of the agreement under which Aberystwyth varieties are licenced).

Whilst plant traits are technically patentable, in order to do this one would need to demonstrate that it had not been produced by an 'essentially biological process'. To date, European case law would indicate that traits arising from selecting plants for crossing (i.e. including via GS methods) are not patentable, whereas a transgenic plant would be. Protecting traits via patents is therefore not a form of protection we are seeking to exploit in the Miscanthus breeding programme.

In other crops, the innovation of GS does not have commercial value; the key exploitable result is the new improved varieties that are bred. The underlying genome selection models are specific to the populations and environments in which they are generated so have little value to others. Notably some companies offering sequencing services also offer services relating to the models themselves.

The breeding programme itself, comprising its foundation germplasm, populations, varieties under development, and expertise are clearly a significant asset that has value (as evidenced by the purchasing of programmes and ongoing investments in them elsewhere in the plant breeding sector).

Appendix 4 – supply side Miscanthus companies

Discussions with Miscanthus supply chain companies contacted during phase 1 are summarised below:

Terravesta: Established in 2012, the business has steadily grown to become recognised as a world leading Miscanthus specialist. They have an annual turnover of £5.5 million, and 16 permanent staff. They offer a growers 10-15 year contract model whereby they buy Miscanthus from farmers for a fixed price (RPIX linked) and sell it on to end users. In 2021 they had 5,000 hectares under contract with 205 growers, and end user contracts with 2 straw fired power stations (Brigg, Snetterton). Terravesta also operate in Europe with rhizome nurseries in Poland, and seed production facilities in Spain. The seed production facilities are overseen by Energene Seeds Ltd. Terravesta Poland was established in 2021 to manage growth in Europe and support EU trade relationships. Terravesta is also active in Moldova, with the expectation of 2000 ha of Miscanthus being planted (as feedstock for biomass boilers for a district heating system). Terravesta have an active interest in new seed-based hybrids and have made significant investments in underpinning research on pre-commercial trials, agronomy development and seed production facilities. They have exclusive rights on Aberystwyth varieties currently undergoing registration testing (detailed in Appendix 3).

Miscanthus Nursery Ltd: Plant/sell Mxg rhizomes and provide after-sales agronomy support, in collaboration with New Energy Farms. Not currently engaged in Miscanthus breeding or variety development. Companies house listings indicates its status as a micro-company.

New Energy Farms: Their main product is an encapsulation technology (CEEDS) which contains primed plant tissue together with growing media. They collaborate with Miscanthus Nursery Ltd on Miscanthus planting and development and did not wish to disclose data on how many hectares they had planted. Companies house listings indicate its status as a micro-company. They would like to have access to future Miscanthus material on non-exclusive terms, and their main interest is in vegetative propagation (as opposed to seed-based hybrids). Not currently engaged in Miscanthus breeding or variety development but seek to import clonal material from other countries.

Crops for Energy: Provider of willow and Miscanthus varieties (predominant business interest is willow). Offers Mxg rhizomes (via a relationship with Miscanthus Nursery Ltd). Provides after-sales agronomy support and consultancy. Not currently engaged in Miscanthus breeding or variety development. Anticipates continuing a similar business model in the future.

Appendix 5 - Sources of funding for R&D underpinning the Miscanthus supply chain

Aberystwyth's work on Miscanthus spans multiple areas of activity, as summarised below.

Activity type	TRL	Revenue sources	Example activities
Fundamental research	1-3	UKRI RM, BBSRC Institute Strategic Funding	Genetic and phenotypic characterisation of key traits, elucidating the underlying biology and physiology of the plant across its life cycle, chemistry and compositional analysis. Genome sequencing.
Pre-breeding	1-4	UKRI RM, BBSRC Institute Strategic Funding	Trait elucidation, initial genomic selection experiments.
Breeding	3-7	Public/private initiatives, Royalty Income	New variety production based on our extensive germplasm collection. Approaches included recurrent selection, paired crossing, open crossing, hybrid creation, multi-location trials.
Agronomy	1-7	Innovate UK, public/private initiatives, H2020	Development of seed production, planting, establishment, ongoing agronomy through the crop life cycle
End uses	2-5	Innovate UK, public/private initiatives, H2020	Applied and fundamental research into the end uses of the plant, including combustion, anaerobic digestion, and incorporation into bio-based products including construction materials.
Commercial upscaling	7 +	Private investment, InnovateUK, H2020	Multi-location trials at field scale, bulk seed production in commercial crossing blocks, marketing, IP protection and CPVO registration trials.
Environmental context	1-3	UKRI, UK Gov	Carbon balance, impacts on biodiversity, flooding, use on contaminated land, ecosystem services
Policy development	N/A	UKRI, UK Gov	Synthesis of the above, modelling to support policy design